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FIGHTER AIRCRAFT OBIGGS STUDY

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The objective of this study was to develop a prototype development plan for installing the best choice OBIGGS in an Advanced Tactical Fighter (ATF). The best choice OBIGGS was based on detailed studies of inert gas requirements for ATF missions and trade-off studies to arrive at the best system preliminary design. Detailed specifications were defined for the best choice OBIGGS and life cycle cost studies were conducted to compare this OBIGGS with other fuel tank fire protection techniques. Results of the mission analysis and preliminary design studies are presented in Volume I; results of the other studies and the prototype development plan are in Volume II. Keywords:

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PREFACE

This is the final technical report of work conducted under AFWAL Contract F33615-35-C-2545 by the Boeing Military Airplane Company, Seattle, Washington during the period from July 1985 through January 1987. Program sponsorship and guidance were provided by the Fire Protection Branch of the Aero Propulsion Laboratory (AFWAL/POSH), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 07, and Work Unit 05. R. G. Clodfelter was the Government Project Engineer. Funds for the contract were provided by the Joint Technical Group on Aircraft Survivability (JTCG/AS).

The final report is contained in two volumes. Volume I contains mission analysis and preliminary design information, together with discussion of the computer code used for mission analyses and trade-off studies in selecting the best-choice OBIGGS. Volume II contains the specifications and prototype development plan for the best choice OBIGGS as well as life cycle cost comparisons of the best choice OBIGGS with other fire protection techniques.

Documentation of the computer programs used to support this contract were provided to the Air force under Boeing Document Number D180-29903-1, "Fighter Aircraft Fuel Tank Inerting Mission Analysis and OBIGGS Design User's Manual," and Boeing Document Number D180-29903-2, "Life Cycle Cost Analysis for Fighter Fuel Tank Explosion Protection System User's Manual."

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1.0 INTRODUCTION AND SUMMARY

1.1 Introduction

Aircraft fuel tank fire protection has been the focus of intensive research for many years because of the importance of protecting the crew and increasingly valuable assets against fuel tank fires and explosions. Without a protection system, the fuel/air mixture in the fuel tank vapor space (ullage) is susceptible to ignition due to combat damage, lightning, electrostatic discharges and electrical arcing resulting from equipment malfunctions.

Several fuel tank protection concepts have been implemented. Many Air Force fighter aircraft are equipped with explosion suppressant foam, a fuel tank void filler material that prevents damaging overpressures by localizing in-tank combustion (Ref. 1). Halon extinguishment systems are used on some Air Force and Navy aircraft (e.g., Ref. 2). Liquid nitrogen (LN_2) systems, which are used on the C-5 airplane fleet (Ref. 3), prevent fires by inerting the ullage (by limiting the oxygen concentration in the ullage to 9% by volume). Although these systems have demonstrated fire protection effectiveness, they each have one or more disadvantages. The foam has weight, installation and maintenance disadvantages. The Halon extinguishant in Halon systems is too costly for full time fire protection and resupplying Halon presents logistics problems. LN_2 systems must be frequently resupplied with liquid nitrogen which also presents fundamental logistics problems, since a minority of air bases have liquid nitrogen production and/or storage facilities.

An alternative to these systems is the on-board inert gas generation system (OBIGGS) that processes engine bleed air into a nitrogen rich gas suitable for fuel tank inerting. Since the inert gas is produced during aircraft operation, the logistics problems of resupply vanish. Furthermore, the OBIGGS has weight and maintenance advantages over the foam system.

Air Force interest in the OBIGGS concept dates back to the 1960's. Technical approaches evaluated included permeable membranes, molecular sieves and catalytic reactors. The latter was soon eliminated from serious contention but considerable work was devoted to developing the other two approaches. The permeable membrane separates oxygen and nitrogen by utilizing a membrane

material that allows oxygen to pass through the membrane much more readily than nitrogen. Molecular sieves create an inert gas by using materials that have a strong propensity to adsorb oxygen as bleed air passes through the sieve material. Since the adsorption effectiveness decreases as the oxygen accumulates, two sieve units are required and used in a process called pressure swing adsorption (PSA). At any given time, one unit is creating the inert gas while the other is being purged of accumulated oxygen.

In 1978 the Air Force awarded Contract F33615-77-C-2023 to AiResearch to design, build and flight test a fuel tank inerting system based on an on-board inert gas generator (Ref. 4). The inerting system developed under this contract was scheduled for flight testing on a KC-135 airplane. However, the Air Force subsequently cancelled the flight test portion of the contract and substituted an in-depth ground test program under a separate contract with the Boeing Military Airplane Company (F33615-78-C-2063). AiResearch was still under contract to provide the Air Separation Module (ASM) and the bleed air conditioning system. Later funding cuts on the AiResearch contract also resulted in the elimination of the air conditioning system from the hardware delivered for ground testing.

AiResearch performed an analysis of the KC-135 inerting requirements and determined that the ASM was required to produce 3 pounds per minute of nitrogen enriched air (NEA) with an oxygen concentration of 5% by volume (NEA_5) and 8 pounds per minute of NEA_9 to inert the wing tanks of that airplane.

The AiResearch ASM was based on hollow fiber permeable membrane technology developed by DOW Chemical Company. An inerting system, capable of meeting the KC-135 requirements, was initially designed on the basis of projected performance from five 13-inch diameter ASM's. However, initial attempts by DOW to produce a 13-inch diameter ASM were not completely successful. DOW eventually produced 9-inch diameter ASM's, and AiResearch delivered a permeable membrane inert gas generator (PMIGG) consisting of five 9-inch units rated at one-half (4 pound per minute of NEA_9) of the original design inerting requirements.

In 1980 the Air Force awarded a contract to the Instruments & Life Support Division of the Clifton Precision Company (Contract F33615-80-C-2007) to produce an alternative ASM (Ref. 5). The Clifton unit used molecular sieves to generate the inert gas. Clifton developed a molecular sieve inert gas generator (MSIGG)

based on Air Force specifications and the AiResearch analysis of the KC-135 inerting requirements. The Clifton MSIGG, as delivered, met the 3 and 8 pounds per minute requirements mentioned previously and underwent the same extensive ground tests as the AiResearch PMIGG (Ref. 6).

Shortly after the permeable membrane and molecular sieve concepts described above were found to be acceptable for aircraft implementation, a TECHNICAL BREAKTHROUGH in ASM technology surfaced. The advanced technology ASM offered the potential for a factor of 10 or more improvement in inert gas production compared with the current technology ASM's of the same size and weight. This breakthrough allowed the realistic application of OBIGGS to fighter aircraft to be considered in studies such as the current one. Prior to this breakthrough, the OBIGGS was thought to have application to only large (bomber/cargo) aircraft Tests at WPAFB have confirmed the predicted factor of 10 performance improvement for advanced technology ASM's. Based on these highly encouraging results, the advanced technology ASM was the baseline ASM for the fighter aircraft OBIGGS studies discussed in this report. Furthermore, a joint Air Force, Navy and JTCG/AS program is currently underway to evaluate OBIGGS using advanced technology ASM's for generalized fighter airplane applications.

Prior to presenting the results of this study, it is appropriate to define the following terms as used in this report:

- Stored gas OBIGGS - An OBIGGS based on a relatively small ASM that generates inert gas at a nearly constant rate, and a high pressure compressor and storage bottle system to provide inert gas as required by the fuel tanks.

- Demand OBIGGS - An OBIGGS that uses an ASM sized for the most demanding inert gas flow rate of the design mission. The ASM is relatively large for the demand OBIGGS but the compressor and storage bottles are eliminated.

- Maximum rate or high speed descent - terms used synonymously to connote the fastest descent that can be made without structural failure.

- Emergency descent - an unplanned descent that could occur at any point in the mission. An emergency descent is not defined in terms of a specific descent profile, since the profile could vary, depending on the reason for the emergency descent.

- ASM or IGG - terms that are used interchangeably to describe the portion of the OBIGGS where the separation of oxygen and nitrogen occurs.

- NEA quality - the quality of NEA refers to the amount of oxygen in the mixture. A characteristic of ASM performance is that the quality decreases (the oxygen concentration increases) as the production rate of inert gas increases. Since the amount of bleed air that is exhausted as waste flow is relatively constant for all inert gas production rates, high quality NEA is produced at the expense of lower inert gas or product flow for a given amount of bleed air flow.

- Aspiscrubbing - a technique for removing dissolved oxygen from the fuel during refueling by mixing the fuel with the ullage gases from the previous flight. The dissolved gases are evolved and vented overboard by a vortex action within a specially designed aspiscrub nozzle. The incoming fuel provides the motive flow and the nozzle design causes the ullage gases to be drawn in and mixed with the fuel. The key to effective aspiscrub operation is the presence of high quality (low oxygen concentration) ullage gases at the start of refueling.

1.2 Summary

The overall goal of the fighter OBIGGS study was to establish a prototype development plan for installing an OBIGGS in an Advanced Tactical Fighter (ATF). Studies to support establishing the development plan included establishing OBIGGS design requirements, conducting a preliminary design for a generic ATF, developing OBIGGS specifications for ATF application, and conducting life cycle cost studies.

1.2.1 OBIGGS Mission Analysis

Mission inert gas requirements were defined by selecting a generic ATF airplane configuration, investigating representative ATF mission profiles and establishing appropriate study ground rules. An air-to-air combat escort mission was found to be the most demanding in terms of inert gas requirements, and approximate (non-optimized) inert gas storage and flow rates were established. The stored gas OBIGGS for the mission required an inert gas generating capacity of 0.7 pound per minute and a storage capacity of 46 pounds of NEA_5; the demand OBIGGS was required to produce a peak inert gas flow of 27.4 pounds per minute with a maximum oxygen concentration of 12% by volume. Both OBIGGS would provide the repressurization requirements for an emergency descent at any time in the mission.

1.2.2 OBIGGS Preliminary Design

The preliminary design involved many trade-off studies to minimize the overall aircraft penalty. For example, a relatively small air separation module could generate relatively large quantities of NEA if the supply air was carefully conditioned. However, the weight and volume penalties of the ECS equipment required could be prohibitive. The basic task was, given the inert gas requirements from the mission analysis task, to optimize the OBIGGS for the mission as well as other operational requirements. The trade-off studies included:

- limited relaxation of the full-time inerting requirement
- stored gas versus demand OBIGGS
- extent of conditioning of supply air versus air separation module performance
- comparison of OBIGGS with other protection systems
- complexity of control system versus OBIGGS sizing
- OBIGGS weight, volume, reliability, maintainability, and airplane and engine penalties
- ground standby and turn around requirements.

The points of departure for the preliminary design studies were the inert gas requirements from the mission analysis task. These will be termed the baseline requirements in subsequent discussions. The baseline requirements assumed that the ullage became uninert during taxi, but that full time

inerting was provided for the rest of the mission. Following revisions based on the trade-off studies, the best choice OBIGGS was a stored gas system that would provide full time inerting, including taxi time. This included normal taxi as well as the reduced taxi time associated with airplanes on alert status and on hot turn around missions. In addition the best choice OBIGGS provided protection for airplanes during 48 hour ground standby. The best choice OBIGGS allowed the generation rate to be reduced to 0.65 pound per minute, but the required storage capacity was increased to 50 pounds of NEA_5. The weight of the system was about 258 pounds and had a volume of about 7.4 cubic feet. A basic disadvantage of the stored gas system is the requirement for a lightweight, 3000 psi compressor, because the reliability of such compressors has been relatively low. An alternative to the stored gas OBIGGS, the demand OBIGGS, was not selected as the best choice because, in spite of basic advantages, its weight penalty did not justify its selection. However, since about 49% of the weight for a demand OBIGGS was for ECS and supply air cooling related equipment, meaningful weight reductions are quite feasible. For example, analysis shows that if the inert gas generator could operate continuously at 160° F with required inert gas flow rates, the ECS weight could be decreased by about 90%. Creative designs could reduce the weight of other components also. In short, although the stored gas OBIGGS was the best choice for this study, the demand OBIGGS would seem to be the better concept. Efforts should continue to reduce the demand OBIGGS weight, especially the development of higher temperature fibers for air separation modules.

1.2.3 Specifications

Specifications were developed for the best choice OBIGGS. Performance requirements were established for the air separation modules and the ancillary equipment, including flow control valves, pressure regulators, heat exchangers and similar equipment. Specification requirements are based on the best available unclassified information on ATF airplane designs. Efforts were made to minimize TBD's (to be determined) but some TBD's were necessary at this juncture. The specification values are subject to change, of course, depending on the evaluation of the OBIGGS concept itself and capabilities of component manufacturers to meet the performance levels specified.

1.2.4 Life Cycle Costs

Life cycle costs were computed for the OBIGGS, liquid nitrogen, Halon and reticulated foam fire protection systems. Without considering the fuel penalty for the extra weight of the protection systems, the foam system had the lowest life cycle costs. However, when the fuel penalty for a fleet of 600 ATF's operating 300 hours a year for 20 years was included, the life cycle costs of the foam system were the highest. The life cycle costs of the Halon system were comparable to the foam system largely due to the high price of Halon.

Both OBIGGS had the lowest life cycle costs with the stored gas being the lowest, even though Halon and LN_2 were the lightest systems. The cost of the LN_2 and manhours to resupply the aircraft after each mission were significant to result in a more costly alternative than OBIGGS.

1.2.5 Prototype Development Plan

The prototype development plan was based on the best choice stored gas OBIGGS and was time phased to match development of the ATF prototype airplanes. The plan assumed that any fundamental problems with the OBIGGS could be identified and corrected by conducting simulated flight testing in the Simulated Aircraft Fuel Tank Environment (SAFTE) facility at WPAFB. The OBIGGS installation on a flight test airplane could then be made with low risk, eliminating the need for a dedicated OBIGGS flight test program.

2.0 OBIGGS STUDY AIRPLANE DESCRIPTION

2.1 Configuration and Performance

The airframe chosen for this study is Boeing ATF Model 908-833 (Figure 1). This airplane utilizes advanced composite materials and subsystems, and features a one man crew, twin engines and canard type controls (Figure 2). The configuration summary of this low altitude, air-to-ground optimized aircraft is as follows:

o Empty weight	32,099 lb
o Operating weight	33,743 lb
o Payload weight	
o air to air	2,160 lb
o air to ground	5,110 lb
o Total fuel weight	19,154 lb
o Unusable fuel	191 lb
o Gross weight	
o air to air	55,057 lb
o air to ground	58,007 lb
o Flight design weight	55,057 lb
o Mach number	
o at sea level	1.2
o at altitude	2.2
o Engine type	Allison Turbojet
o Bypass ratio	0.0
o Number of engines	2
o Take-off thrust	47,495 lbs

2.2 Fuel System Description

This airplane has 3 body tanks and 2 wing fuel tanks with a total of 409.8 cubic feet (3066 gallons) (Figure 3). The fuel system is similar to the F-15, featuring:

- o Refuel valves in each tank (5 total)
- o Separate vent lines from each tank

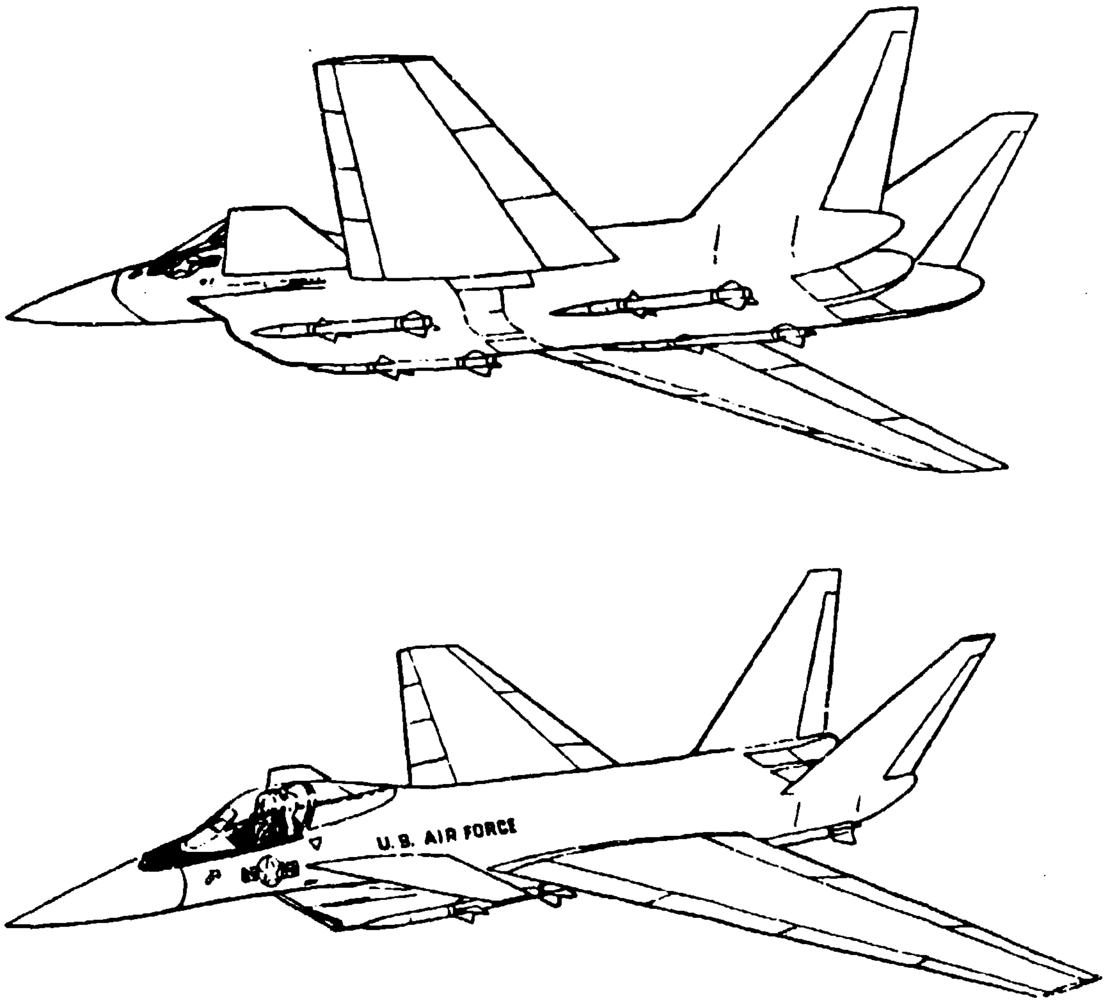


Figure 1. Boeing ATF Model 908-833

Materials		
GR/TP 32.7%	• Spars • Ribs • Bulkheads	• Frames • Stringers • Longerons (partial)
GR/BIS 27.3%	• Fuselage • Wing	• Control surface skins
Titanium 15.5%	• Fittings • Splices • Fasteners • Spindles • Wheels	• Air-induction • Mechanisms • Engine supports and surrounding hot structure • Longerons (partial)
Aluminum 1.0%	• Fittings	• Splices
Steel 6.3%	• Landing gear	
Other 17.2%	• Radome • Canopy • Tires	• Paint • Sealant
100%		

GR = Graphite
BIS = Bismaleide (thermal set)
TP = Thermoplastic

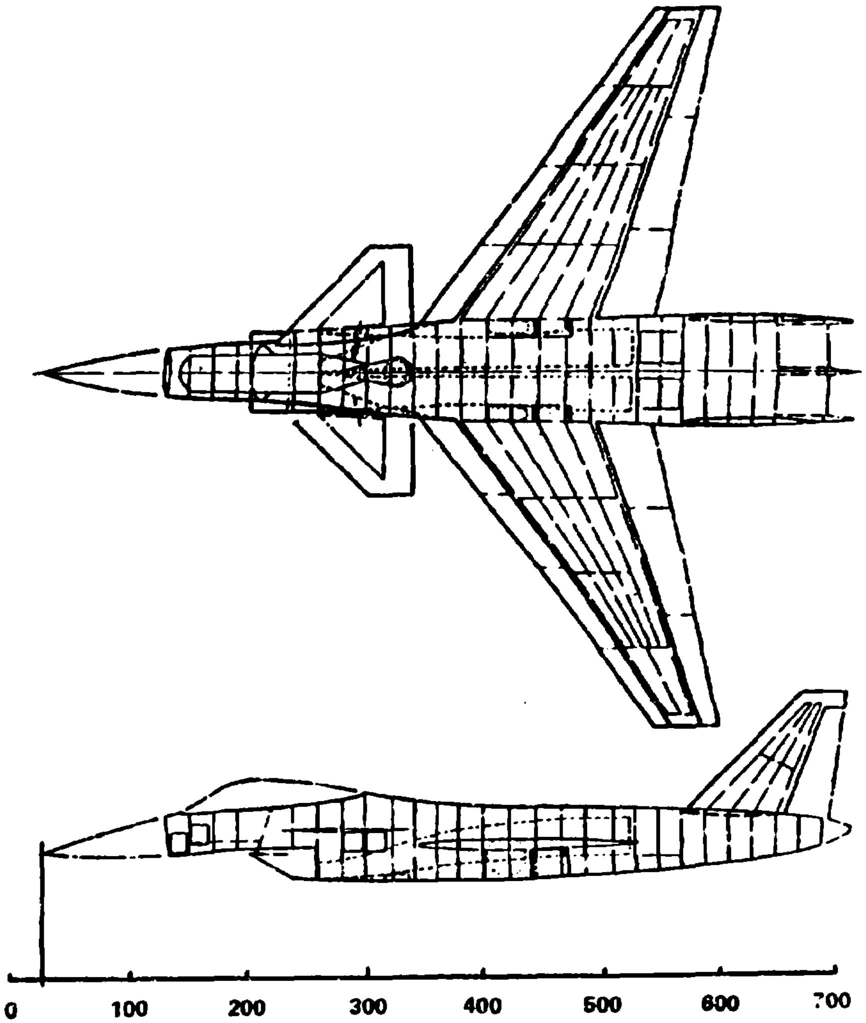
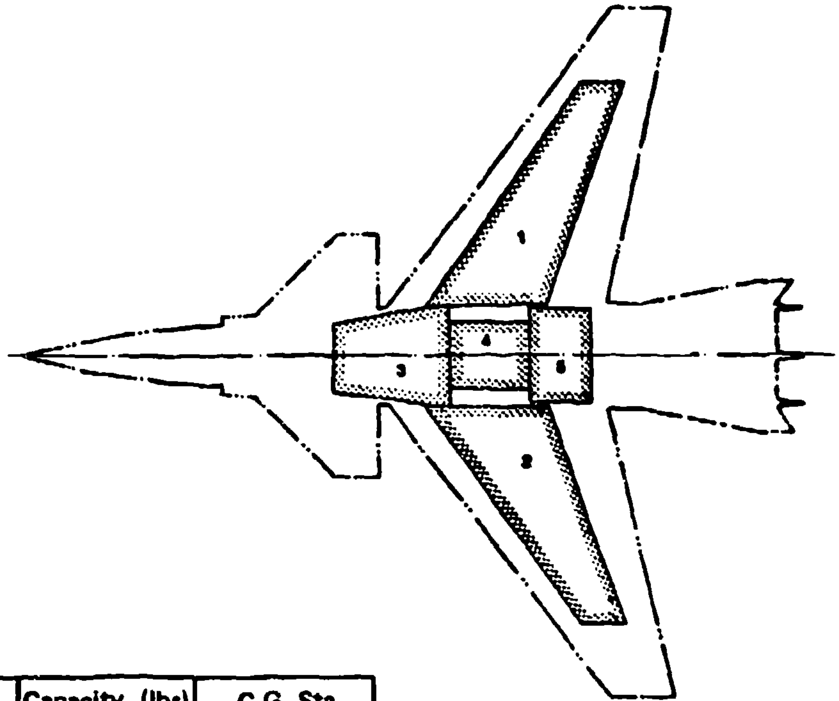


Figure 2. Structural Arrangement and Material Breakdown for Boeing ATF Model 908-833



Tank	Capacity, (lbs)	C.G. Sta.
1	2,872	470
2	2,872	470
3	7,859	350
4	1,753	440
5	3,990	496
Total	19,345	

Figure 3. Fuel Tank Arrangement for Boeing ATF Model 908-833

- Vent box in each wing
- Separated transfer lines and refuel lines
- Single point refueling and defueling
- Aerial refueling system compatible with KC-135 and KC-10 tankers

The pressurization schedule and the dive valve setting are the same as the F-16, normal mode:

- Climb valve setting = +6.4 psig
- Demand regulator setting = +4.7 psig
- Dive valve setting = -0.75 psig

The climb valve setting controls the maximum overpressure in the tank by venting ullage gases whenever the tank pressure reaches the climb valve setting. Similarly, the dive valve opens to allow atmospheric air to enter the tanks whenever the tank underpressure is equal to the dive valve setting. The demand regulator allows inert gas to flow to the tank whenever the tank pressure is less than the demand regulator setting.

The fuel tanks are vented to atmosphere during refueling and ground operations.

2.3 Internal Storage

The OBIGGS and the aircraft Environmental Control System (ECS) are located in an aft fuselage bay of the generic ATF as shown in Figure 4. The volume of this bay, which is approximately 19.5 cubic feet, established the upper limit on the volume of the OBIGGS including the ECS.

2.4 Threat Protection

Previous tests have shown that peak overpressures resulting from hydrocarbon explosions in an unprotected fuel tank are greater than 100 psig for a 50-cal API rounds, electrical spark (Ref. 7) and 23 mm HEI rounds penetrating fuel tank (Ref. 8). But the same studies showed that in a nitrogen inerted ullage, where the oxygen concentration is below 9-10%, measured overpressures are 10 psig or less for 50-cal API (Ref. 7) and 23 mm HEI (Ref. 8). This is within acceptable levels for most fuel systems.

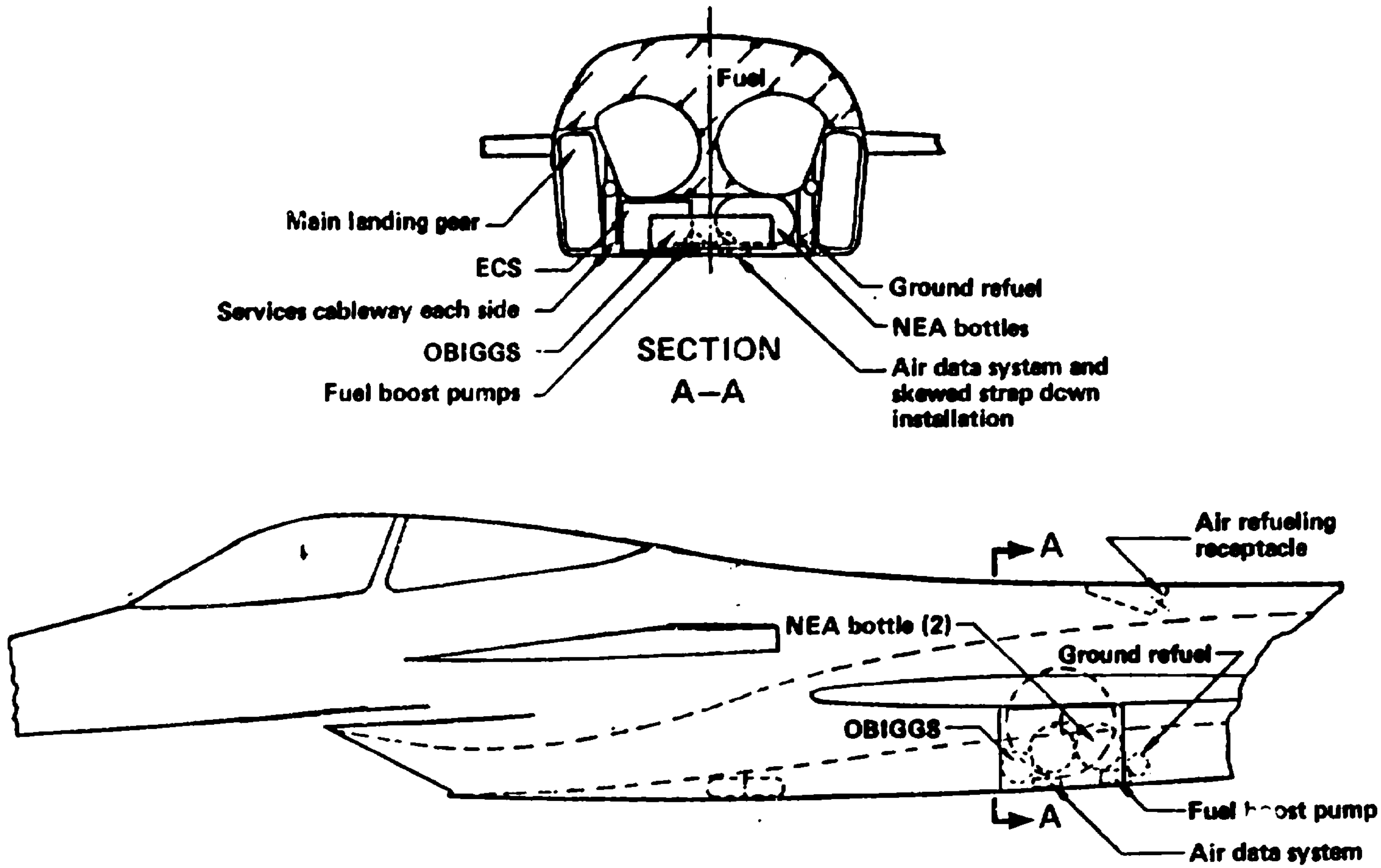


Figure 4. Fueselage Compartment Holding the OBIGGS for Boeing ATF Model 908-833

Therefore, if inerting is provided, structural failure from threats up to 23 mm HEI could be avoided. Full-time inerting could also protect against explosions from electrostatic discharge, lightning strikes and other combat induced damage for both the entire mission profile and a 48 hour ground standby time.

3.0 MISSION ANALYSIS

3.1 Mission Profiles

The objective of the mission analysis study was to select the mission that would place the greatest demands on the OBIGGS to ensure that the OBIGGS was adequately sized. The primary mission characteristics considered were:

- o number and rate of descents
- o altitude excursions of the descents
- o ullage volume and temperature.

Other factors which influenced OBIGGS sizing were:

- o fuel scrub and/or washing requirements
- o inerting while on ground standby
- o repressurization schedule including dive valve settings
- o fuel burn rates.

A total of 12 missions were evaluated (Table 1). The first three were combat missions taken from the Propulsion Assessment for Tactical Sytems (PATS). The next eight were training missions compiled from the Life Utilization Criteria Identification in Design (LUCID) study. Both the PATS and LUCID Studies were sponsored by the Air Force. Missions from the PATS and LUCID studies were chosen because they were representative examples of various realistic and unclassified war and peace time mission scenarios for modern fighter aircraft. The last mission was selected from a simulation of an escort intercept scenario using a BMAC code called "Advanced Air-to-Air System Performance Evaluation Model" (AAASPEM). The scenario consisted of four typical ATF aircraft providing escort for a F-15 airplane on a low level ground attack mission. Additional details of the mission profiles for the missions indicated on Table 1 are documented in Appendix A.

OBIGGS mission analyses were based on two Boeing computer codes. The first was the "Airplane Fuel Tank Thermal Analysis" (AFTTA) which predicts ullage and fuel bulk temperature time histories (Ref. 9). For this study AFTTA

TABLE 1. GENERIC ATF MISSION SUMMARY

Mission Type	Number of descents	Descent Rates (ft/min)	Fuel Burn Rates (lb/min)	Duration (min)
PATS Mission 1	4	3,491 to 3,840	29.7 to 986.6	126.0
PATS Mission 2	4	3,500 to 3,968	31.5 to 917.0	136.5
PATS Mission 3	3	3,483 to 3,500	64.5 to 608.9	126.1[2]
LUCID Mission 1A	15	369 to 40,022	145.0 to 1,893.3	70.9
LUCID Mission 1B	12	370 to 38,167	108.3 to 1,947.5	136.4[1]
LUCID Mission 2A	4	370 to 8,333	65.3 to 1,852.5	80.5[1]
LUCID Mission 2B	6	370 to 8,333	66.1 to 1,468.3	144.1[1]
LUCID Mission 3A	9	370 to 1,606	109.8 to 1,433.3	86.4
LUCID Mission 3B	10	370 to 8,333	110.1 to 1,433.3	170.2[1]
LUCID Mission 4A	9	370 to 8,974	171.1 to 1,489.4	82.4[1]
LUCID Mission 4B	15	370 to 8,333	108.7 to 1,468.3	166.9[1]
Escort Intercept Scenario	4	22,000 to 33,000	35.1 to 2,080	107.0[2]

[1]With aerial fueling

[2]Worst case mission

was modified as follows:

- o The convection heat transfer coefficient for the fuel was evaluated as a function of fuel temperature

- o Conductive and convective heat transfer coefficients and emissivities for the fuel tank walls were changed to model a representative composite material and construction

- o Tank structural elements were modeled

- o The radiation heat transfer model was enhanced to account for solar radiance and sky emittance.

The temperature time histories output of this code was used as inputs to the fuel the second computer code which is the "Fuel Tank Inerting Mission Analysis" (FTIMA). This code predicts the repressurization mass and flow rate requirements for the mission assuming instantaneous and homogeneous mixing and ideal gas behavior (Ref. 10). This code also predicts the ullage oxygen concentration time history resulting from repressurization gas and wash and/or scrub gas, based on performance maps obtained from testing ASM's under simulated flight conditions. This code was used extensively for trade-off studies as well as mission analyses. The FTIMA code is discussed in more detail in Appendix B.

3.2 Ground Rules and Assumptions

The analyses in this task were based on several key assumptions, to provide a common datum for mission analysis.

The assumptions included:

- o full time inerting with a maximum allowable ullage oxygen concentration of 9% throughout entire mission, including an emergency descent; short periods of uninert time over friendly territory would be considered if this significantly reduced the size of the system

- the stored gas OBIGGS concept was the baseline system
- NEA with 5% oxygen (NEA_5) for fuel tank inerting (output from the OBIGGS)
- JP-4 fuel.

The following paragraphs list the study ground rules and discuss the rationale for each.

1. Full time inerting with a maximum allowable ullage oxygen concentration of $\leq$ 9% throughout the entire mission, including an emergency descent, was the design objective.

   Rationale: Fuel tank fire and explosions can be prevented from combat threats up to 23 mm HEI and natural threats such as electrostatic discharge and lightning if the ullage oxygen concentration is 9% or less.

   Part-time inerting can offer significant weight savings, and has been implemented on F-16 airplanes. However, based on a previous study (Ref. 10), the weight savings for a part-time OBIGGS did not justify its choice over a full-time system.

   Allowing the ullage to become uninert during taxi/takeoff was a preliminary tradeoff to reduce weight. A more detailed trade study to identify the increased risk of uninert ullage during taxi and takeoff and the associated system weight tradeoffs are discussed in Section 4.

2. A stored gas OBIGGS was the baseline for trade studies.

   Rationale: The most severe inert gas requirements usually accompany high speed descents. An OBIGGS designed to produce inert gas on demand during a high speed descent would be oversized for the rest of the mission. The alternative is a stored gas system. In the stored gas system, inert gas is accumulated in a high pressure storage tank during flight segments when the required inert gas flowrates are low, and used when inert gas flowrates are large. As presented later, a demand system may be feasible using advanced technology air separation modules for a generic ATF. However, only

preliminary performance data are currently available from a small demonstration unit. Extrapolating the advanced PHIGG performance and weight to provide the large flow rate requirements for a demand system must be done with caution until better data are available. This does not mean the demand system was rejected at this juncture; a comparison of the demand system with the stored gas system is presented in Section 4, based on performance.

3. The use of NEA with 5% oxygen (NEA_5) was assumed for fuel tank inerting.

Rationale: The range of NEA qualities can range from pure nitrogen (NEA_0) to NEA_9 to prevent the ullage oxygen concentration from exceeding 9%. A characteristic of the OBIGGS is that the oxygen concentration increases as the inert gas flow rate increases. In a previous Boeing study, the overall performance penalties for NEA_5 and NEA_7 were compared (Ref. 10). The NEA_7 stored gas system was lighter but required 50% more scrub gas (see Section 4.3 for discussion of scrubbing), negating most of the weight benefit. The conclusions were that NEA_5 was superior because:

- NEA_5 would maintain a safe ullage if one storage bottle was damaged in a two storage bottle system, where NEA_7 would not
- NEA_5 would be superior to NEA_7 if aspiscrubbing (see Section 4.3) was used.

4. JP-4 fuel was the baseline fuel.

Rationale: JP-4 fuel was chosen as the baseline fuel over JP-5 and JP-8 because of the higher solubility of oxygen in JP-4. Previous studies revealed that this additional scrub gas required for JP-4 more than offset the advantage of JP-4 vapors in aiding the inerting process.

3.3 Inert Gas Flow Requirements

The 12 candidate OBIGGS sizing missions were surveyed to select the missions with the highest inert gas flow requirements based on the number of descents, rate of the descents and the magnitude of the altitude excursions. The down selection process yielded five missions that required additional study:

- the three PATS missions

- o training mission 1B (from the LUCID study)
- o the escort intercept scenario (the last entry on Table 1).

For convenience throughout the remainder of the report, the five study missions were labeled A through E (Table 2).

TABLE 2. STUDY MISSIONS DEFINITION

Mission Label	Source	Mission Type
A	PATS Mission 1	air-to-air combat
B	PATS Mission 2	high altitude air-to-ground
C	PATS Mission 3	low altitude air-to-ground
D	LUCID Mission 1B	subsonic weapon delivery training (proficiency)
E	Escort Intercept Scenario	air-to-air combat

Several basic factors were considered in the analysis process. The repressurization schedule and dive valve settings had a direct effect on the rate and mass repressurization requirements. The maximum allowable taxi time could effect scrub requirements. The nominal NEA quality could effect all the requirements. The fuel tank sizes and ullage volumes had a large bearing on the mission requirements. Mission dependent input data, such as fuel quantity, ullage volume and temperature time histories are shown in Appendix C.

3.3.1 Fuel Scrubbing

An analysis was performed to determine the minimum flowrate and mass of scrub gas required to ensure an inert ullage by the end of the taxi for the study missions. The following assumptions were used:

- o the initial ullage oxygen concentration was either 9% or 21%
- o scrub gases were vented to ambient pressure during taxi
- o the fuel was air saturated at sea level pressure at the initial temperatures listed below
- o the initial fuel temperature was
  - o 59° F for a standard day

- o 0^{o} F for a cold day

- o the fu.l scrubbing efficiency was 90% based on test data. (A 100% efficient scrub nozzle displaces dissolved gases at the same rate that scrub gases are added to the fuel).
- o the ullage oxygen concentration could rise above 9% during taxi and initial climb out
- o scrubbing commenced at time zero in the mission and terminated at the end of the initial climb out
- o the fuel was scrubbed with NEA_5 at a constant quality and flowrate
- o the pressurization schedule was activated at takeoff
- o the climb valve setting was +6.4 psig
- o the demand regulator setting was +4.7 psig.

The initial tank pressure was found to be a significant factor in achieving an inert ullage status. To demonstrate this point, the fuel for the Mission C airplane was scrubbed with 0.55 pound per minute NEA_5 at standard day conditions. The ullage oxygen concentration was below 9% at the end of taxi when scrubbing and venting the gases at ambient pressure (Figure 5). However, the ullage was not inert until 39 minutes into the mission when scrubbing at the climb valve setting (+6.4 psig). Therefore, in all the mission analyses the fuel was scrubbed at ambient pressure and the pressurization schedule was activated at takeoff.

The baseline system for removing dissolved oxygen from the fuel was climb scrubbing by bubbling nitrogen enriched air (NEA) through scrub nozzles on the bottom of each tank. Other inerting schemes such as ullage washing (with NEA) and aspiscrubbing (see Section 1.1 for definition) either as separate or hybrid systems were also investigated.

Successive iterations of the fuel tank inerting code showed that scrub gas requirements varied only by small amounts from mission to mission for two reasons:

- o the missions had the same taxi time, and initial fuel loading, and similar initial climbout conditions

- o short climbs to high altitudes required only slightly more scrub gas than longer climbs to low altitudes.

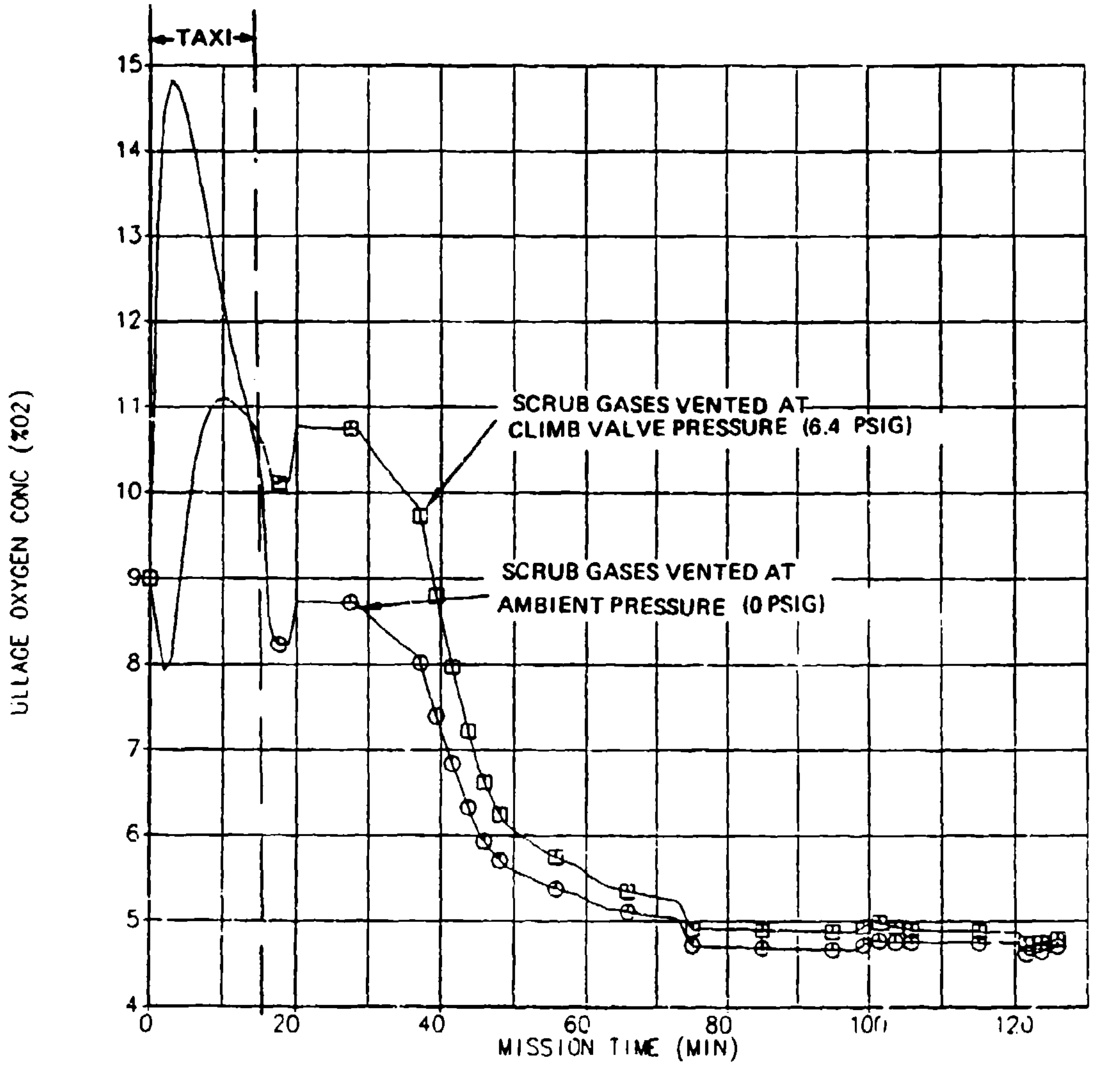


Figure 5. Effect on Ullage Oxygen Concentration When Venting Scrub Gases at 0 psig and 6.4 psig for Mission C on a Standard Day

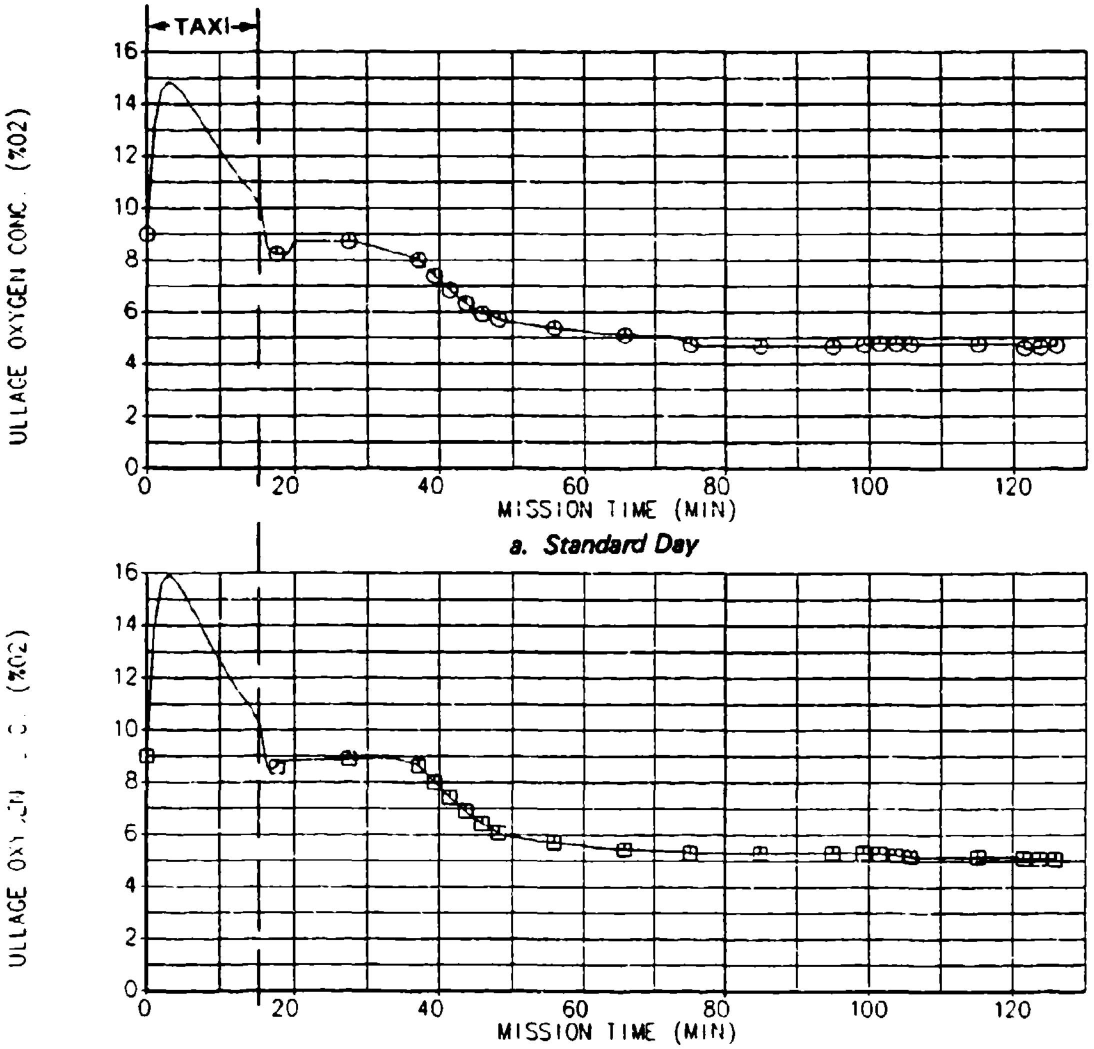
The amount of scrub gas required was about 10 pounds for a standard day and about 14 pounds for a cold day. A representative ullage oxygen concentration history for the study missions (Figure 6) indicates oxygen concentrations well below the 9 percent limit throughout the mission; similar data are contained in Appendix D for the remaining missions. The initial ullage oxygen had little effect on the scrub requirements. Analysis for Mission E on a cold day revealed that the ullage was inert by the end of the taxi for an initial ullage of 9% or 21% for the same scrub gas flow rate (Figure 7). For this ullage volume, air (21% oxygen) in the ullage had no impact on scrub gas requirements.

3.3.2 Descent Repressurization

Fuel tank descent repressurization requirements were evaluated for selected missions using the Fuel Tank Inerting Mission Analysis code. The study variables were repressurization gas requirements (mass) and repressurization gas mass flow rate requirements as functions of mission time for standard and cold days. The assumptions for the analysis were:

- the repressurization gas was NEA_5
- the F-16 pressurization schedule was activated at take-off and maintained throughout the mission
  - climb valve setting: +6.4 psig
  - demand regulator setting: +4.7 psig
- the minimum internal tank pressure was +4.7 psig (demand regulator setting) after take-off
- the dive valve did not open (based on a dive valve setting of -0.75 psig)
- the initial fuel temperature for a standard day was 59^{o} F
- the initial fuel temperature for a cold day was 0^{o} F
- standard day temperatures were based on the U.S. Standard Atmosphere (1962)
- cold day temperatures were based on MIL-STD-210A
- 213 BTU/min were added to the fuel by onboard sources

Each mission analyzed was evaluated assuming fuel usage based on an airplane performance analysis (see Appendix C for fuel usage profiles). The repressurization requirements are summarized in Table 3 for standard and cold days. The missions with the greatest repressurization mass requirements were Missions C and E (Figures 8 and 9) where the mass requirements were 56 and 54 pounds, respectively. Mission E was shorter than Mission C but required a 14



a. *Standard Day*

b. *Cold Day*

Figure 6. Ullage Oxygen Concentration for Mission C (Standard and Cold Day)

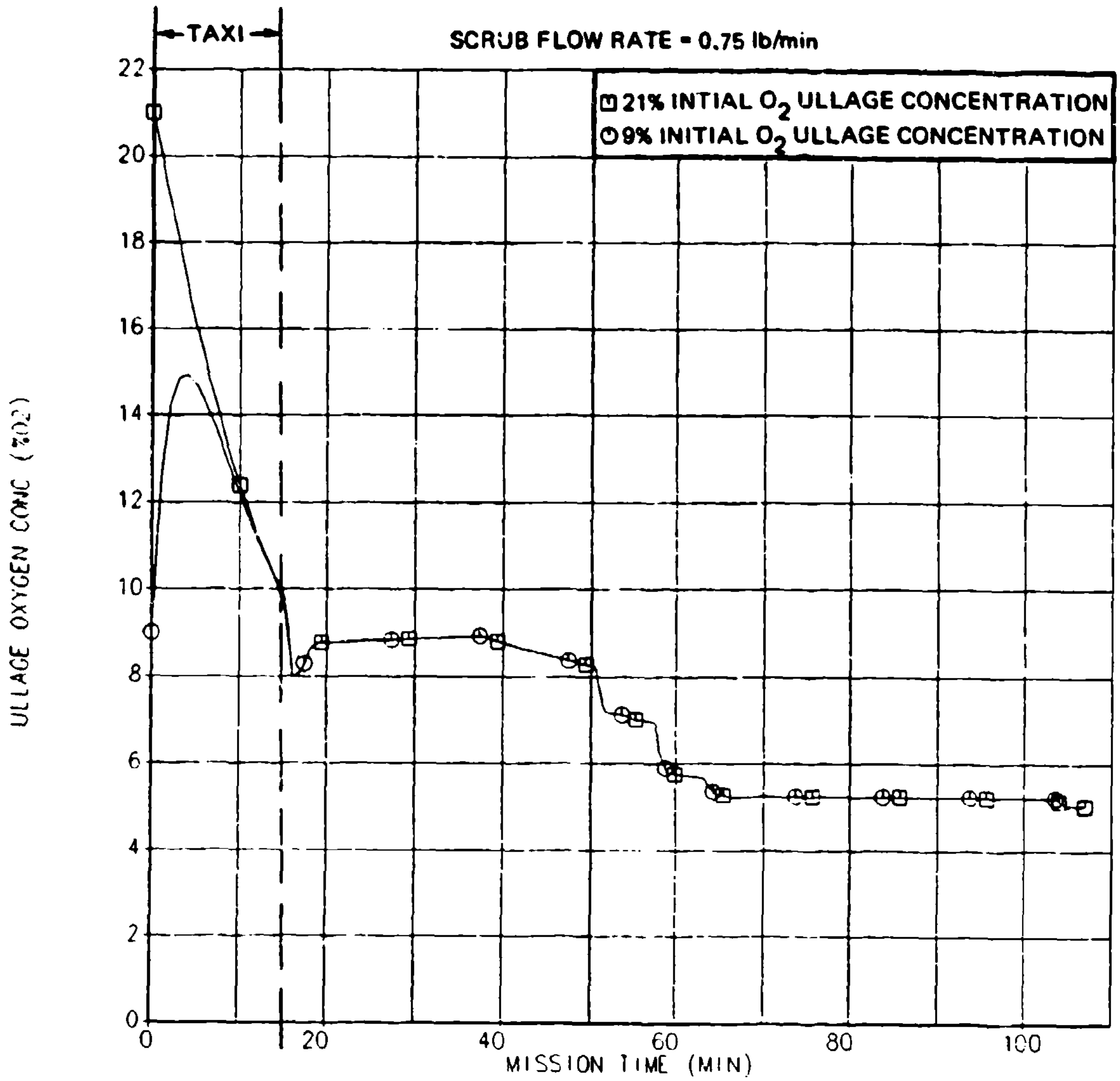


Figure 7. Ullage Oxygen Concentration Profile for Mission E for Initial Ullage Oxygen Concentration of 9% and 21%

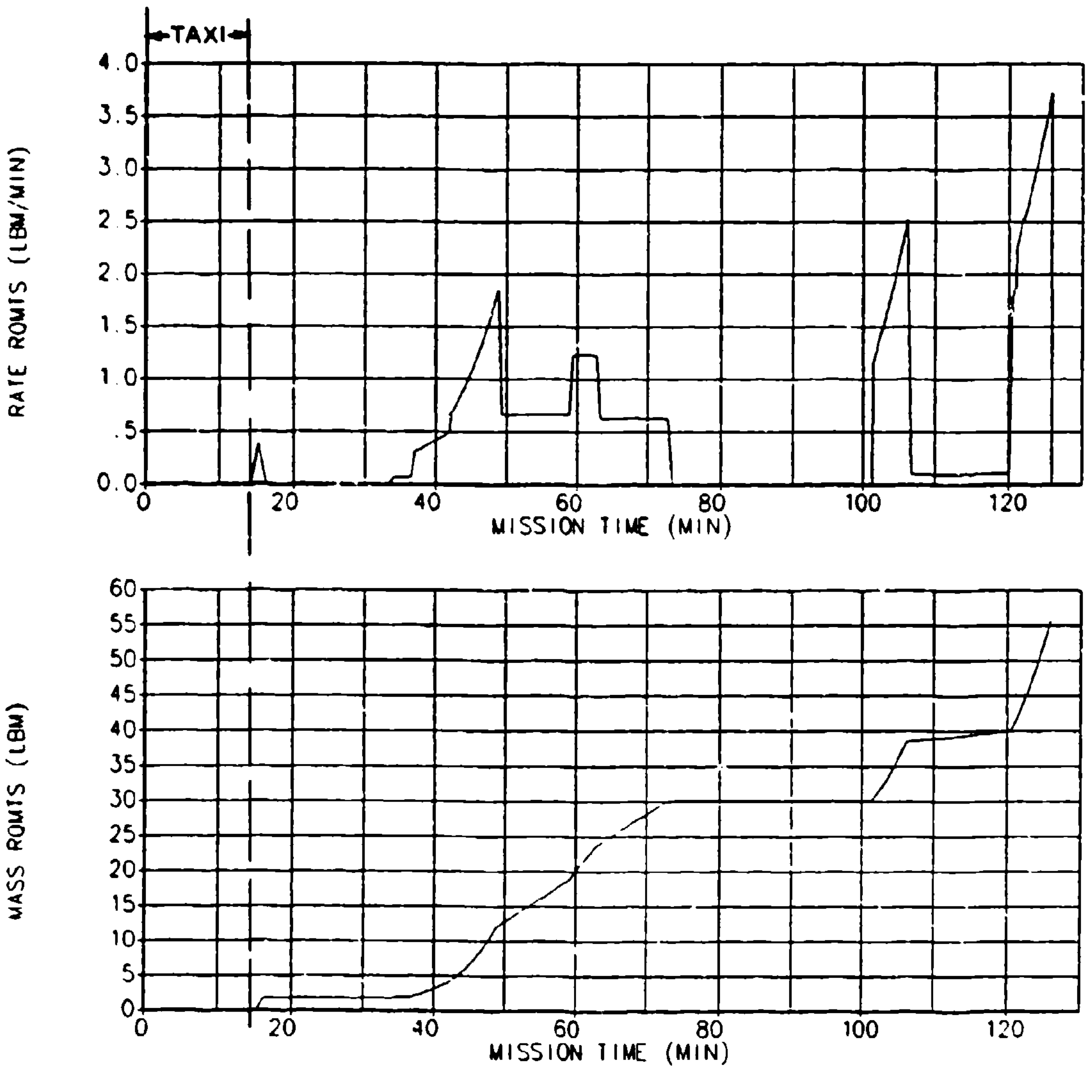


Figure 8. Repressurization Requirements for Mission C (Cold Day)

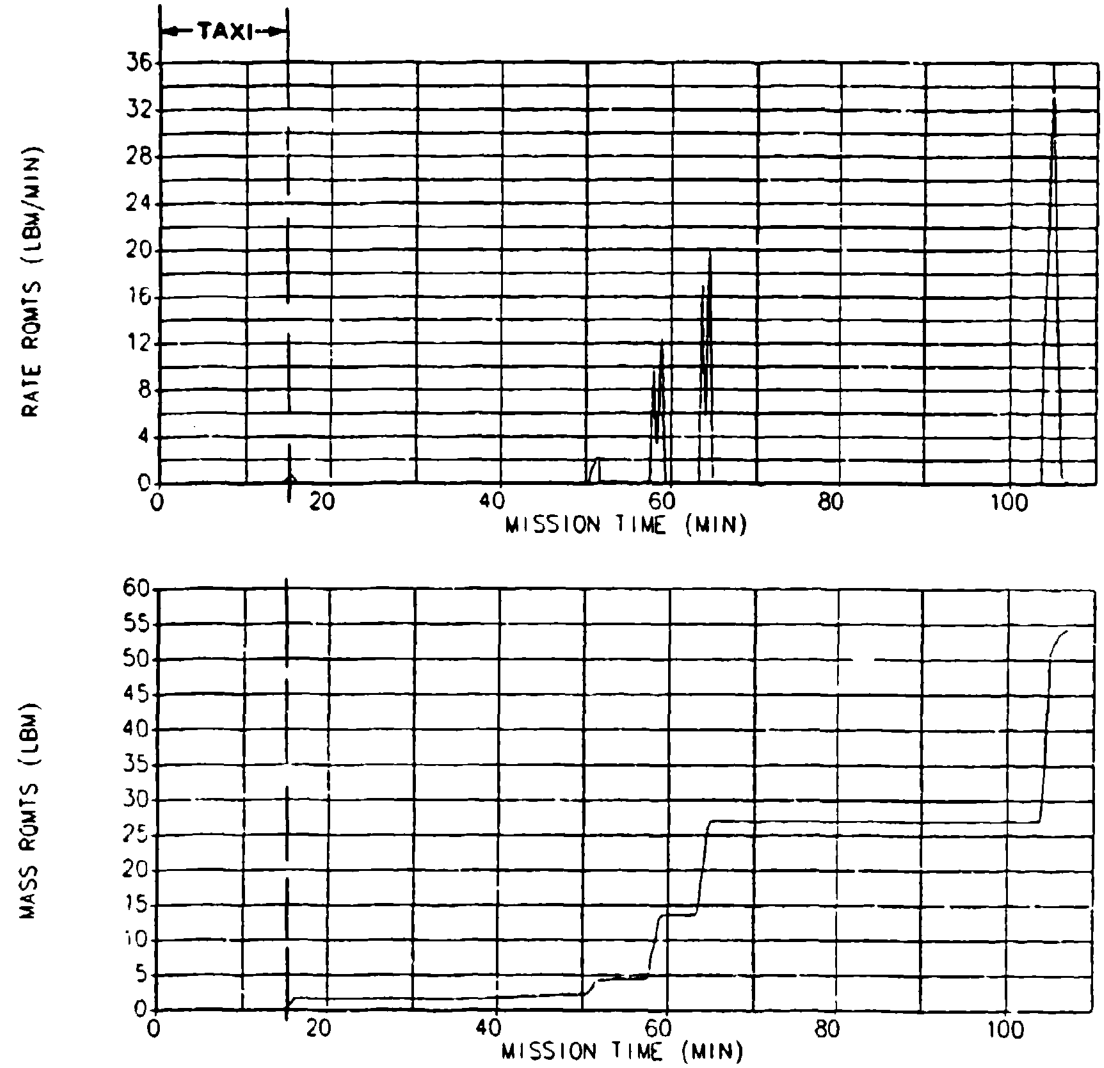


Figure 9. Repressurization Requirements for Mission E (Cold Day)

percent higher mission NEA generation rate though the total mass of NEA required was slightly less. Therefore Mission E (see Figure 10) was chosen as the OBIGGS design mission for the baseline stored gas OBIGGS. Mission E was not included in the original set of missions forwarded to the Air Force for review. The Air Force desired a mission with more climbs and descents than the missions proposed. Accordingly, Boeing developed a combat engagement mission that was satisfactory to the Air Force; this mission became Mission E. Total mass requirements for the five missions analyzed are summarized in Table 3, based on graphical data presented in Appendix E.

TABLE 3. SUMMARY OF DESCENT REPRESSURIZATION REQUIREMENTS

Total Mass of NEA Required (lb)

Mission	Standard Day	Cold Day
A	33	---
B	32	---
C	47	56
D	43	51
E	45	54

3.3.3 Maximum High Speed Descent

A stored gas OBIGGS is relatively insensitive to descent rate since the supply line sizes can be enlarged as required to provide a given flow rate. However, the maximum descent rate is a key variable in defining a demand OBIGGS. Therefore, a study of maximum ATF descent rates were made.

A BMAC operational analysis group, in conjunction with the Boeing ATF group, defined an unclassified maximum descent rate for a typical ATF. This worst case descent started at 75,000 feet at approximately Mach 2.2, turning vertical at 60,000 feet (Figure 11). The airplane began a maximum "G" pullout from a vertical altitude at 10,000 feet at Mach 1.5 and leveled out at sea level. The maximum descent rate was 117,000 feet per minute and occurred at about 50,000 feet.

The repressurization flowrate can be evaluated by the following form of the ideal gas law equation:

$$\dot{m} = \frac{\dot{p}\ V\ 144}{RT} \qquad (1)$$

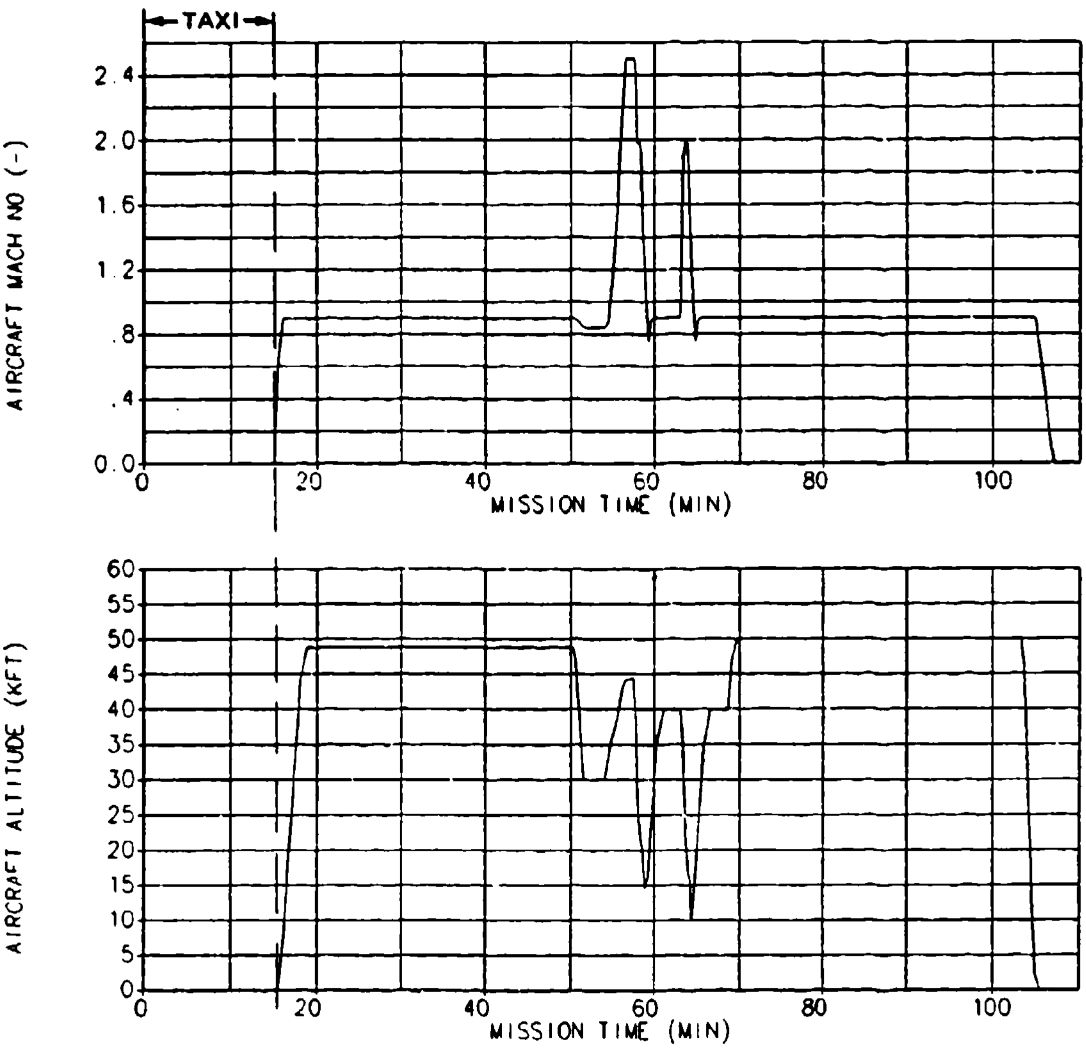


Figure 10. OBIGGS Design Mission Profile Mission E

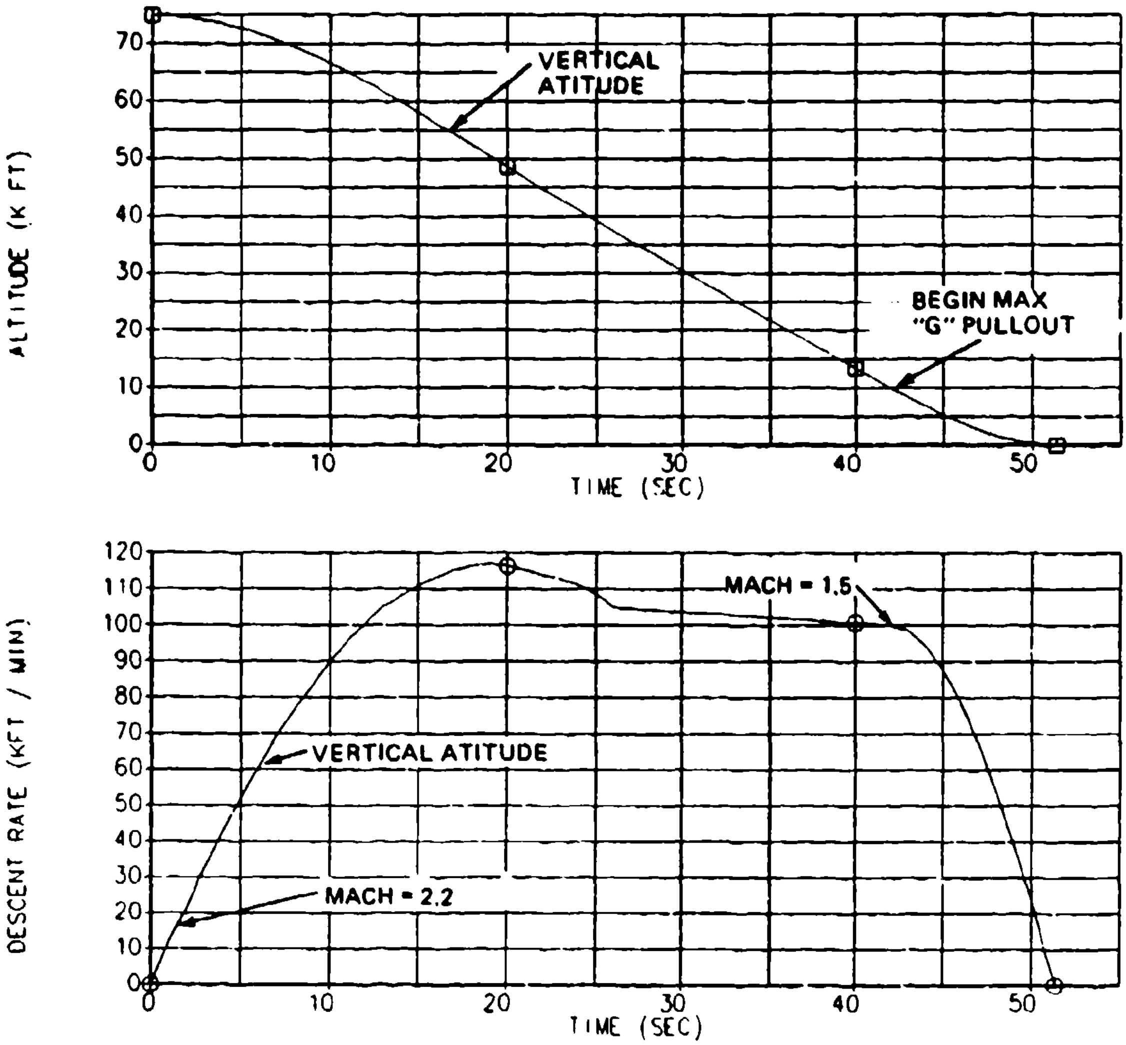


Figure 11. Maximum Descent Rate Profile

where:

$\dot{m}$ = required mass flow rate of repressurization gas (lbm/min)

$\dot{p}$ = rate of change of internal tank pressure (psi/min)
V = ullage volume (370 ft^3)
R = gas constant (54.5 ft $lb_f/lb_m{}^oR$)
T = ullage temperature (520^o R)

Past studies have shown that a constant temperature may be assumed for descent repressurization (Ref. 10). p can be evaluated by (assuming constant tank gauge pressure):

$$\dot{p} = \frac{\delta \, Pamb}{\delta t} = \frac{\delta \, Pamb}{\delta \, alt} \; \frac{\delta \, alt}{\delta t} \qquad (2)$$

where:

$\frac{\delta \, Pamb}{\delta t}$ = time rate of altitude pressure change (psi/min)

$\frac{\delta \, Pamb}{\delta \, alt}$ = rate of change of pressure with respect to altitude (psi/kft)

$\frac{\delta \, alt}{\delta t}$ = descent rate (kft/min)

The maximum instantaneous repressurization rate occurs at 7,200 feet at a descent rate of 95,900 feet per minute assuming constant airspeed at 100,000 ft/min about a circular path to level out at sea level.

Evaluation of Equations 1 and 2 yields p = 41 psi/min and a required repressurization gas flowrate of 77 pounds per minute to maintain a constant tank gauge pressure. This can be reduced significantly by allowing the internal tank gauge pressure to decrease during the descent. For example, assuming that the initial tank pressure is equal to the demand regulator setting (+4.7 psia) and the final pressure is equal to the dive valve setting (-0.75 psig), p can be determined graphically (Figure 12). The slope of the line tangent to the internal tank pressure curve (+4.7 psig) intersecting final tank pressure at the end of the descent (dive valve setting) is the minimum pressure change required to preclude the dive valve from opening. Under these conditions, p is 14.6 psi/min and the corresponding flow rate is 27.4 lb/min.

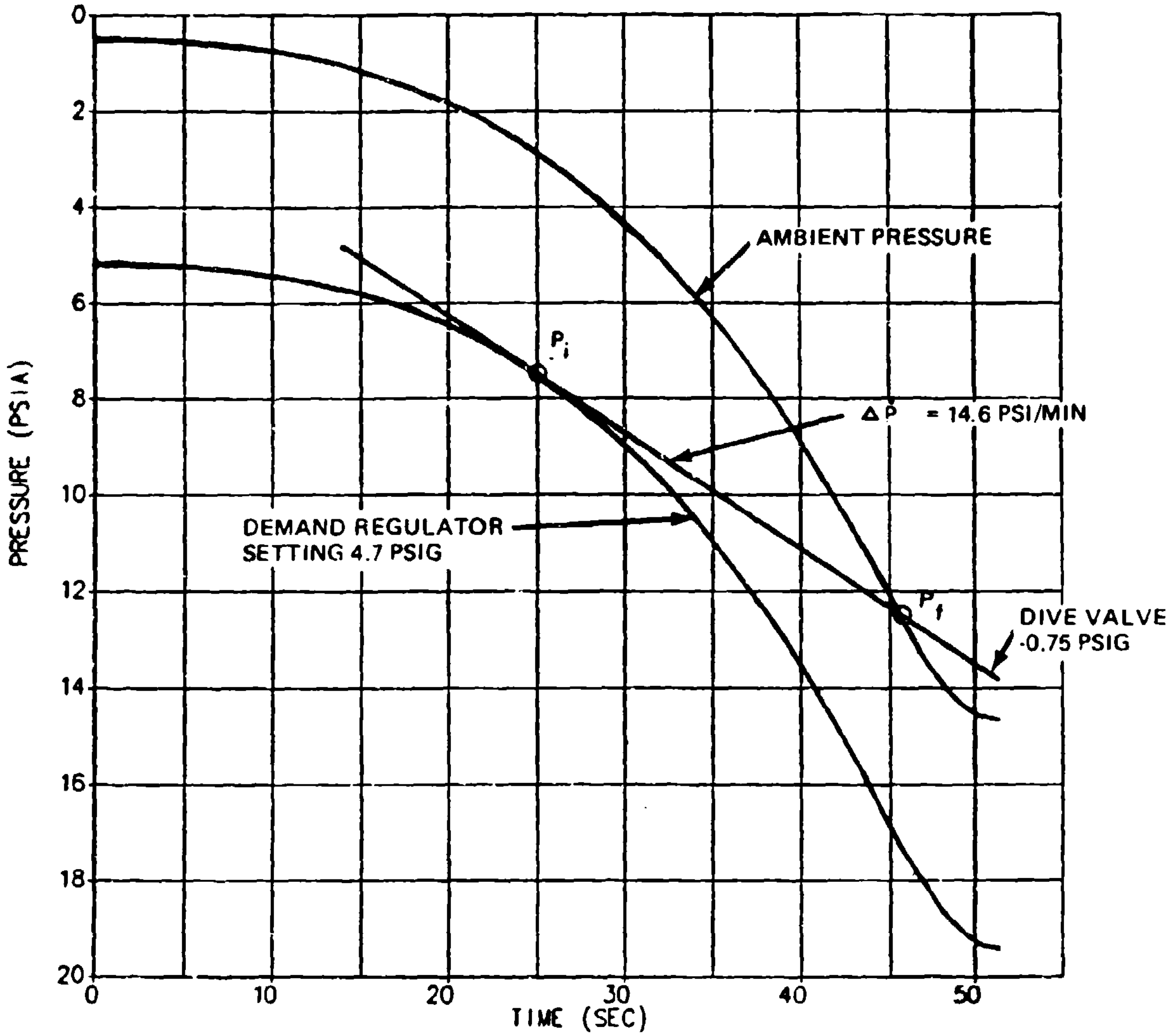


Figure 12. Ambient and Internal Tank Pressure Time History for the Maximum Descent Rate Profile

3.3.4 Emergency Descent

The OBIGGS sizing requirements were based on full time inerting throughout the mission. Therefore, the demand OBIGGS was sized for the max mum rate of descent and the stored gas OBIGGS was sized to meet the repressuriza ion requirements of an emergency descent (see Section 1.1 for definition) at any point in the mission. The quantity required is, therefore, mission specific, and is best evaluated from a total system approach that is discussed in Section 3.4.

3.3.5 48-Hour Ground Standby

In some cases it may be required to protect the airplane during a 48 hour ground standby period. If so,

- additional inert gas would have to be stored from previous mission for a stored gas OBIGGS
- the APU, engine(s) or external high pressure air source would be required to provide inert gas with a demand OBIGGS.

To quantify the 48 hour ground standby requirements, an analysis was conducted based on results of measured fuel temperature cycles for aircraft parked at air bases on extremely hot and cold days (Ref. 11) and JP-4 fuel densities (Ref. 12).

The results of the analysis showed that about 2 pounds of inert gas would be required to maintain an inert ullage for a 48-hour ground standby period.

3.4 Inert Gas Production Requirements

3.4.1 Stored Gas OBIGGS

The major mission dependent criteria for sizing the stored gas system components (the ASM, storage bottle, HP compressor and the associated equipment to cool the supply bleed air) were the total mass of inert gas needed to meet repressurization requirements, scrub requirements, emergency descent requirements and a 48-hour standby. The repressurization gas flow rate requirements affect only the plumbing sizing downstream of the storage bottles. As previously stated, Mission E (cold day) had the greatest inert gas storage requirement and was the OBIGGS design mission.

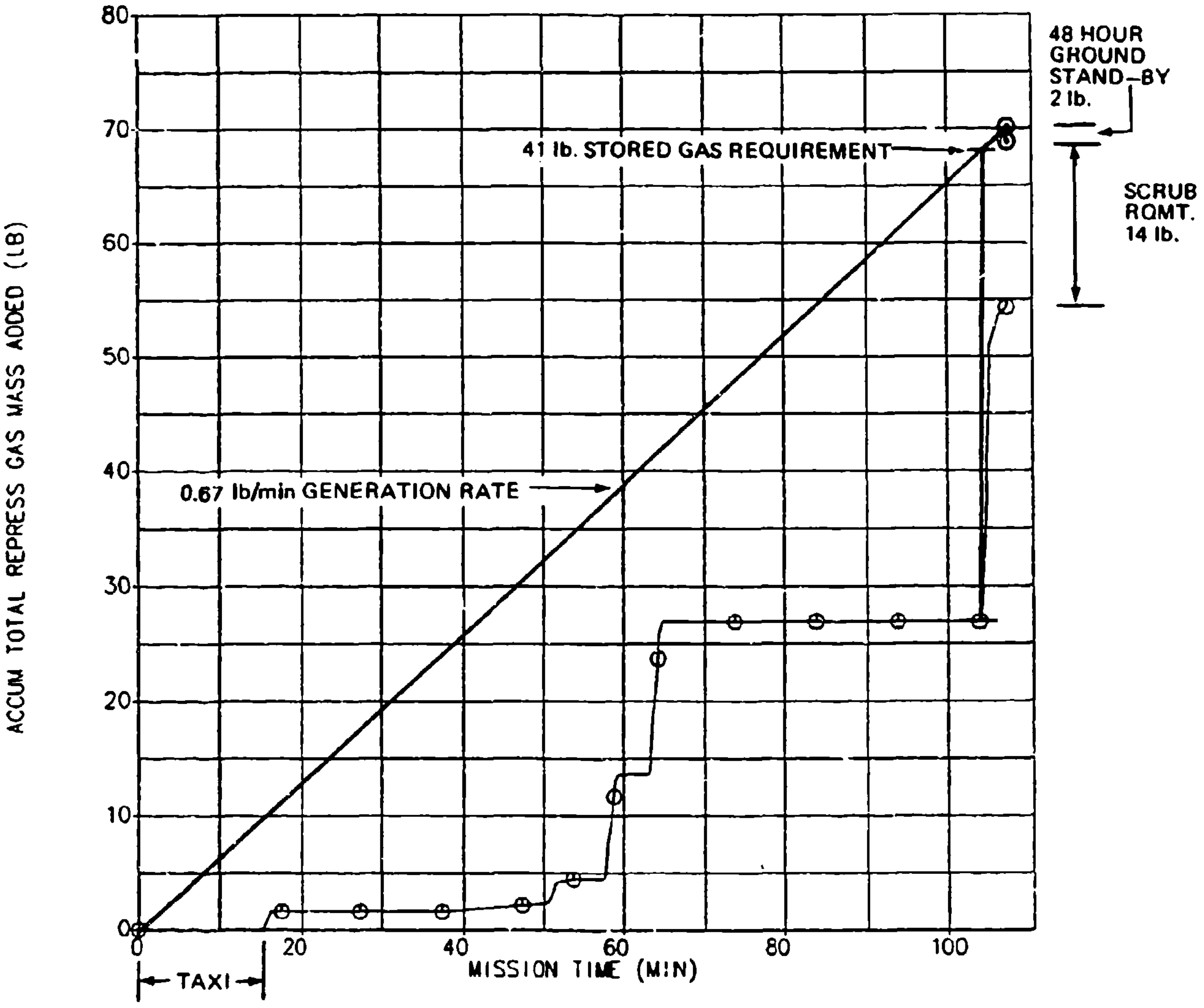


Figure 13. Total Inert Gas Generation Requirements for Mission E (Cold Day)

The minimum flow rate of the ASM and minimum storage bottle size were determined graphically by plotting the accumulated total repressurization gas requirement as a function of time (see Figure 13). The total amount of inert gas for the mission was determined by adding scrub gas and the 48-hour ground standby requirements to the mission inert gas requirements. (Inert gas required for scrubbing and a 48-hour standby were generated during the previous mission). The slope of the line from the origin to the resulting total mission requirement defined the minimum generation rate requirement. The minimum bottle storage size was given by the maximum difference between the generation rate line and the accumulated total inert gas requirement curve. Examination of Figure 13 shows that to satisfy a normal mission, the generation rate requirement is 0.67 pounds per minute, and the storage requirement is 41 pounds, based on the difference between the generated and required inert gases at a mission time of 103 minutes. However, if an emergency descent occurred at the top of climb at a mission time of 70 minutes, 29 pounds of inert gas would be required for tank repressurization. This is four more pounds than would be stored up to that time (Figure 14). The generation rate required to provide for an emergency descent was 0.70 pound per minute. At this constant generation rate, 75 pounds would have been produced by the end of the mission. The total mission requirement at the end of the mission was 72 pounds. This was 3 pounds less than the total available to capture all the NEA produced, creating a need for a storage capacity of 46 pounds.

3.4.2 Demand OBIGGS

The demand OBIGGS was sized to meet the repressurization rate requirements of a maximum descent while maintaining a safe ullage. As previously stated, by allowing the internal tank pressure to decrease to the dive valve setting, the minimum instantaneous repressurization rate of 77 pounds per minute can be decreased to 27.4 pounds per minute for the maximum descent rate profile. Furthermore, the NEA quality could be as high as 12% because the large ASM delivered inert gas with quite low oxygen concentrations when flow rates were low, resulting in a low ullage oxygen concentration first prior to the descent. Therefore, the demand OBIGGS based on the mission analysis study was sized to produce 27.4 pounds per minute of NEA_{12}. As discussed in Section 4, the size of the demand OBIGGS was reduced even further during the preliminary design phase of this study.

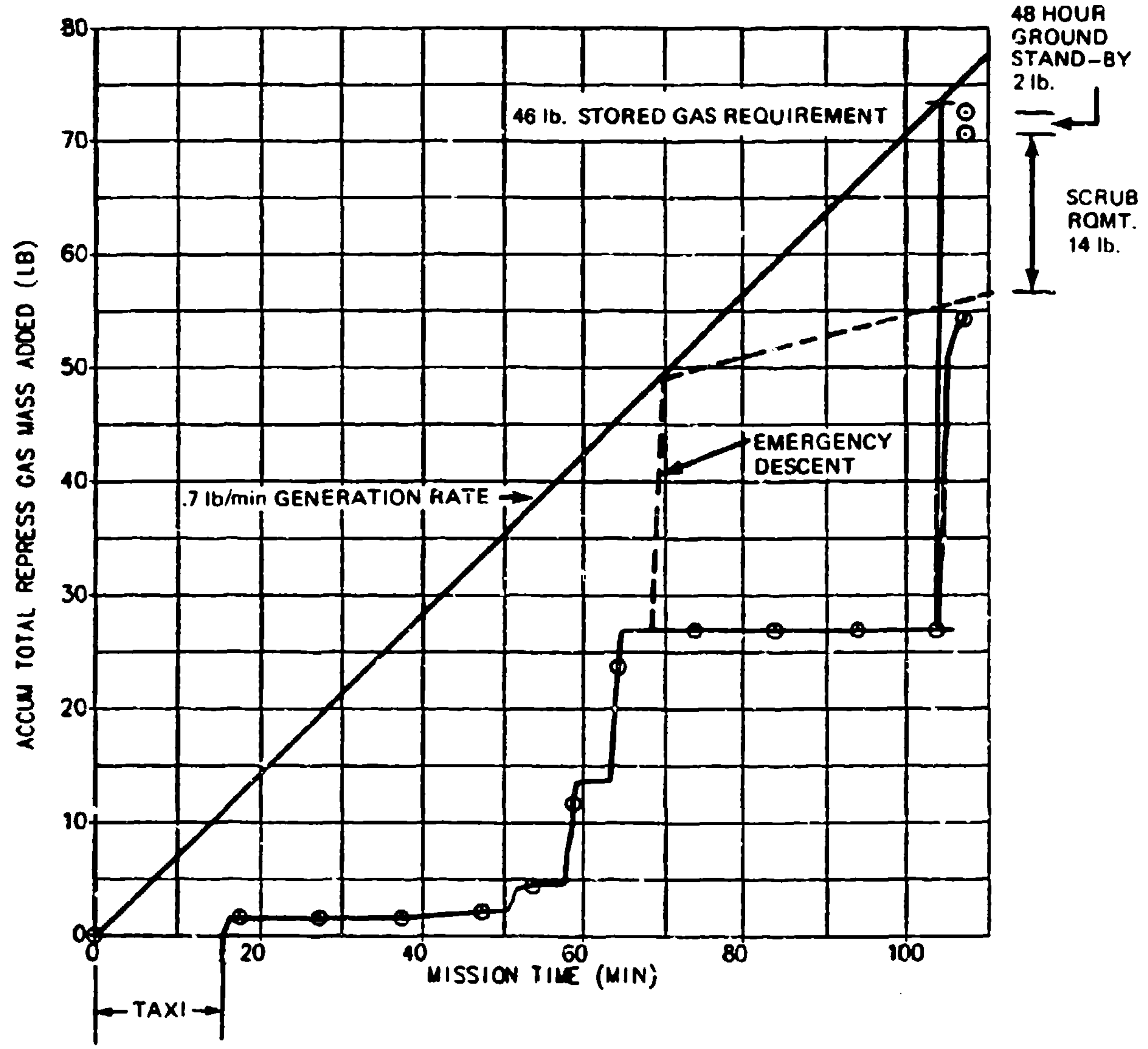


Figure 14. Total Inert Gas Generation Requirements for Mission E (Cold Day) with Emergency Descent Requirements

3.5 Preliminary Air Seperation Module Sizing

3.5.1 Stored Gas System

The stored gas system utilizes a relatively small ASM, generating product gas at a nearly constant rate throughout the mission. The NEA is accumulated in high pressure storage bottles for use as needed for repressurization requirements. A schematic for a stored gas system is shown in Figure 15.

Preliminary OBIGGS sizing data are presented in Table 4. Results shown for current technology MS and PM OBIGGS were based on a previous study (Ref. 13). Results for the advanced technology PM OBIGGS were based on data scaled up from tests on laboratory sized modules.

Table 4. Preliminary ASM Sizing for a Stored Gas System for NEA_5

ASM Type	Inlet Pressure (psig)	Inlet Temperature (^{o} F)	ASM Weight (lb)
MS (current techology)	50	70	74
PM (current techology)	75	70	82
PM (advanced technology)	60	60	7

3.5.2 Demand System

The demand OBIGGS is inherently less complex because a compressor and storage bottles are not required. The inert gas flow rate is controlled by the demand regulator to maintain the required pressure in the tank. Since flow rates are based on demand, when there is no make up gas required the entire OBIGGS may be deactivated, eliminating bleed flow and minimizing airplane penalties. The flow diagram for a demand system is shown in Figure 16.

Of the three IGG unit types (Table 5), only the advanced PMIGG is feasible for a demand OBIGGS for the generic ATF. Weights and volumes for the current technology MS and PM ASM's were scaled from a previous Boeing study (Ref. 13) for a system designed to meet the requirements of a KC-135 (8 lb/min of NEA_9). Table 5 shows the scaled ASM weights of these units and the advanced technology ASM to deliver 27.4 pounds per minute of NEA_9 or NEA_{12}.

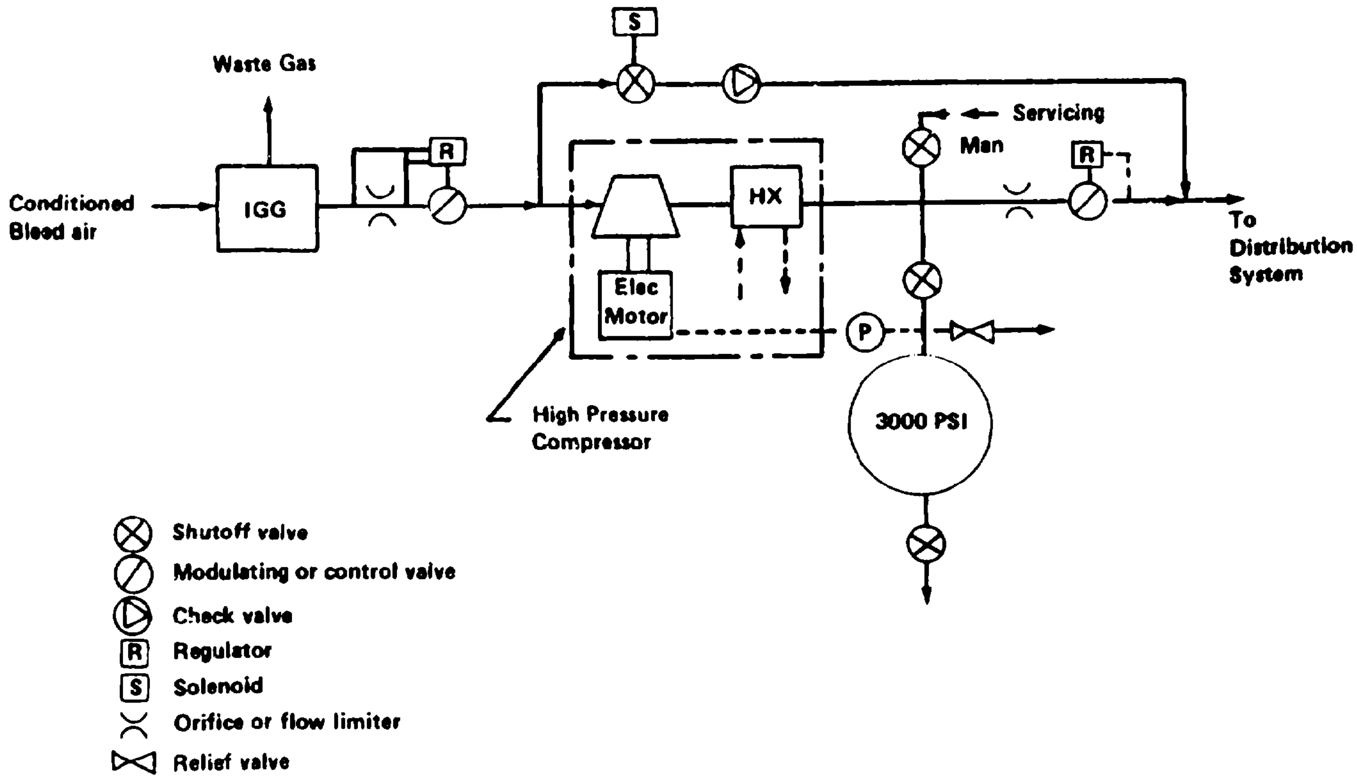


Figure 15. Stored Gas OBIGGS Flow Diagram

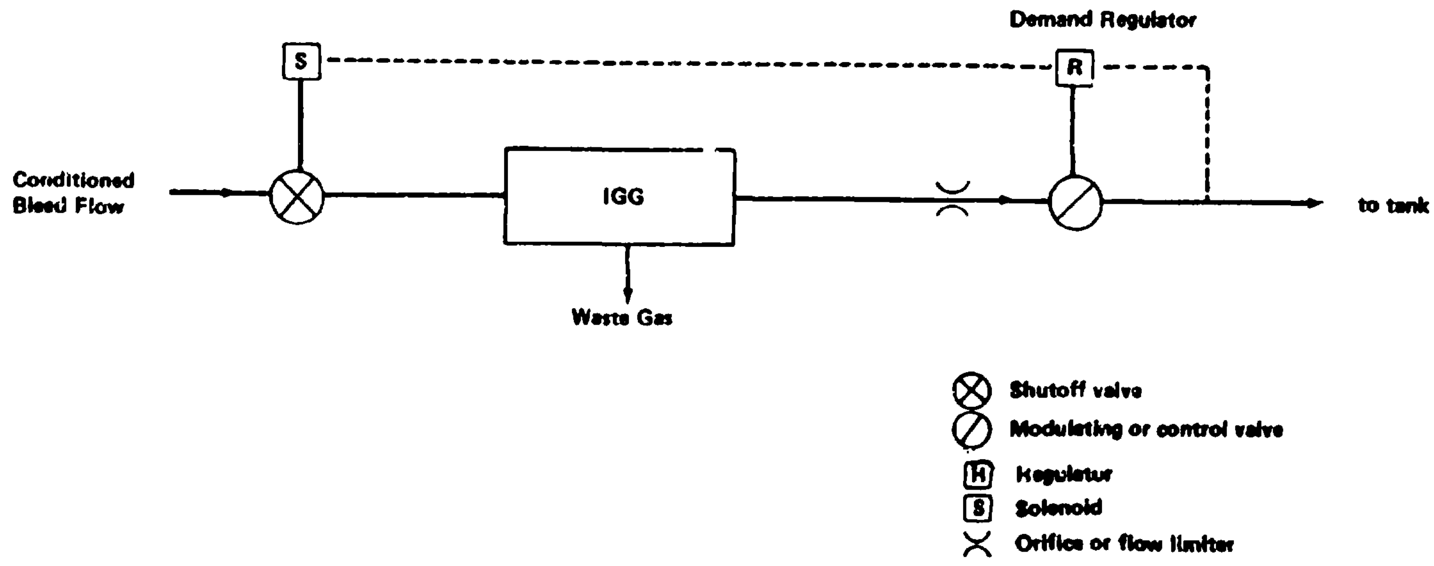


Figure 16. Demand OBIGGS Flow Diagram

Table 5. Preliminary ASM Sizing for a Demand System

ASM Type	NEA Quality (% O_2)	Inlet Pressure (psig)	Inlet Temperature (° F)	ASM Volume (ft^3)	ASM Weight (lb)
Current MS	9	50	70	44.7	1196
Current PM	9	75	70	85.4	1572
Advanced PM	9	70	60	7.4	124
Advanced PM	12	70	60	4.5	79

With an upper limit of 19.5 ft^3 for the OBIGGS compartment, current technology units would be much too large. This factor in addition to the marked difference in weight made the advanced PM OBIGGS the only viable choice for a demand system. As previously stated, a demand OBIGGS may be sized for NEA_{12} output at this high flow rate. The weight saving of 45 pounds (Table 6) between product flows of NEA_{12} and NEA_9 is significant. This lighter ASM was considered in designing the optimal demand OBIGGS.

The major problem with a demand system is sizing the ECS and the associated equipment to cool the supply bleed air, because conditioning up to 50 pounds per minute of bleed air may be required. A capacitance concept is currently being evaluated to condition high quantities of air for short periods of time, using the heat capacity of an expendable such as glycol or water. A characteristic for most of the ASM units is that, for a given set of inlet conditions, the waste gas flow rate is essentially independent of product flow rate. Therefore, avoiding operating at low product flow rates is important in minimizing engine bleed air and other airplane penalties. A more complex control scheme and system to reduce system size at lower flow rates in order to decrease the bleed flow requirements was also investigated in the OBIGGS preliminary design study (Section 4).

In summary, the mission analysis studies established the starting point for trade-off studies to optimize the fighter aircraft OBIGGS. The baseline system was a stored gas OBIGGS with a capability of generating 0.67 pound per minute of NEA_5 and an inert gas storage capacity of 41 pounds (except for emergency descent considerations where the OBIGGS requirements was 0.70 pound per minute of NEA_5 and storage capacity of 46 pounds). The alternate system was a demand OBIGGS with the capabiltiy of producing 27.4 pounds per minute of NEA_{12}. The sizing condition for the demand OBIGGS was a maximum rate descent at the end of the mission.

4.0 OBIGGS PRELIMINARY DESIGN

The trade-off studies leading to the best choice OBIGGS preliminary design for fighter aircraft is described in this section. Initially, it was planned to develop optimal preliminary design for both current technology PM and MS OBIGGS. Subsequently, the advanced technology permeable membrane ASM (see Section 3) showed sufficient promise to be the ASM of choice for the best choice OBIGGS defined in this study. Current technology PM and MS OBIGGS were studied previously for ATF airplane application (Ref. 10). Significant findings included:

- demand OBIGGS units using current technology PM and MS air separation modules would be too large to fit within the space available on ATF airplanes and were weight prohibitive

- stored gas OBIGGS units using current technology air separation modules were feasible for ATF airplane installations.

In contrast to these findings, the factor of ten or more reduction in size and weight of advanced technology air separation modules allowed a demand OBIGGS to be feasible for ATF application and allowed installation of a smaller and lighter weight ASM for a stored gas OBIGGS.

Topics addressed in the preliminary design included:

- stored gas and demand OBIGGS
- fuel scrubbing requirements
- ullage oxygen concentrations
- ground standby
- taxi time
- hot and cold day operation
- multiple hit protection/threat
- full time versus part time inerting
- risk of allowing the ullage oxygen concentration to temporarily rise above the safe limit
- system redundancy
- engine bleed air and airplane ram air requirements
- comparison of OBIGGS with other fire protection systems.

The advanced technology OBIGGS was optimized in terms of weight, volume, reliability, maintainability, supportability and mission penalties based on the results of trade-off studies discussed below.

The baseline mission for the preliminary design study was the escort intercept mission involving air-to-air combat described in Section 3. The baseline inerting system was an OBIGGS that produced and stored NEA_5. The climb (6.4 psig) and dive (-0.75 psig) valve settings were the same as the F-16 airplane and the demand regular setting was 4.7 psig. The demand regulator allowed inert gas to flow to the fuel tanks whenever the pressure decreased below the demand regulator setting. Fuel scrubbing was achieved using the climb scrubbing technique with 90% efficient scrub nozzles in the bottom of the tank. The storage bottles were sized to provide scrub gas for the next mission and sufficient inert gas for a 48 hour ground standby. The trade-off studies were based on comparing various alternatives with a baseline OBIGGS. The baseline system was a stored gas OBIGGS with an inert gas generation rate of 0.67 pound per minute and a storage requirement of 41 pounds of NEA_5.

The ASM performance data were based on a constant supply air pressure and temperature of 60 psig and 95° F respectively. Since 60 psig air was not always available from engine bleed air, a boost compressor was included in the baseline designs (this was the conclusion of a preliminary weight trade study).

4.1 Stored Gas and Demand System Trade-Off

The decision on whether the stored gas or demand ASM should be specified for the best choice fighter aircraft OBIGGS was based on the same factors as the overall OBIGGS (weight, volume, airplane performance penalties, reliability, maintainability and supportability).

Since the ASM in a stored gas system produces inert gas at a nearly constant rate throughout the mission, the design of the portion of the ECS that provides conditioned air to the ASM is simplified. Furthermore, since the flow is steady, a relatively small ASM is adequate. Finally, it is simplier to obtain full time fire protection with a stored gas OBIGGS. The disadvantage of the stored gas system lies in the high pressure compressor and storage bottles required. The compressors will almost certainly increase maintenance requirements for the OBIGGS and could cause logistics problems and increased airplane down times. The high pressure storage bottles are a potential additional hazard in the event of combat damage to the OBIGGS compartment.

The demand system is attractive because of its basic simplicity. When based on the permeable membrane concept, the system produces inert gas without the compressor and storage bottles required for a stored gas or the switching valves required for a molecular sieve device. The major disadvantage is that the demand OBIGGS must be sized for the maximum flow rate of the mission, resulting in a relatively large ASM unit. In addition, since the flowrate may change considerably over the mission, the ECS must respond quickly in terms of providing properly conditioned bleed air. Another unknown is the effect of transients on inert gas flow rates. The analysis assumes that the ASM instantaneously adjusts to changes in inert gas requirements. However, this needs to be verified by tests.

The objectives in the preliminary design phase were to optimize both the stored gas and demand OBIGGS for fighter airplane application, then to compare the resulting designs to judge which concept was the better for this application.

4.2 Ullage Oxygen Concentration

Test data such as those shown in Figure 17 reveal that the peak combustion overpressure rises rapidly as ullage oxygen concentrations increase above 9%, the maximum percentage for fuel tank safety. With certain notable exceptions, maintaining oxygen concentration at safe levels presents no significant problems. These exceptions are following: refueling, high speed descents and ground standby. Since relatively large amounts of dissolved oxygen may enter the fuel tanks during refueling, this oxygen must be removed in a controlled manner to prevent oxygen contamination of the ullage. Test data reveal that scrub nozzles are about 90% efficient (see Section 3.3.1) which causes a significant percentage of dissolved oxygen to be evolved early in the scrubbing phase, and produces the tendency for oxygen concentration profiles to exceed 9% for a brief period of time. Although development would be required, using inefficient scrub nozzles could remove the undesirable bump in the oxygen concentration curve. High speed descents adversely impact ullage oxygen concentrations if the inert gas flow rate is not sufficient to prevent the dive valves from opening. This presents no basic problem for a stored gas OBIGGS, since only the line sizes of the inert gas distribution system are affected. However, the descent rate directly impacts the size of air separation modules for a demand OBIGGS. These modules must be sized to provide flow rates required for tank repressurization under the most severe descent requirements.

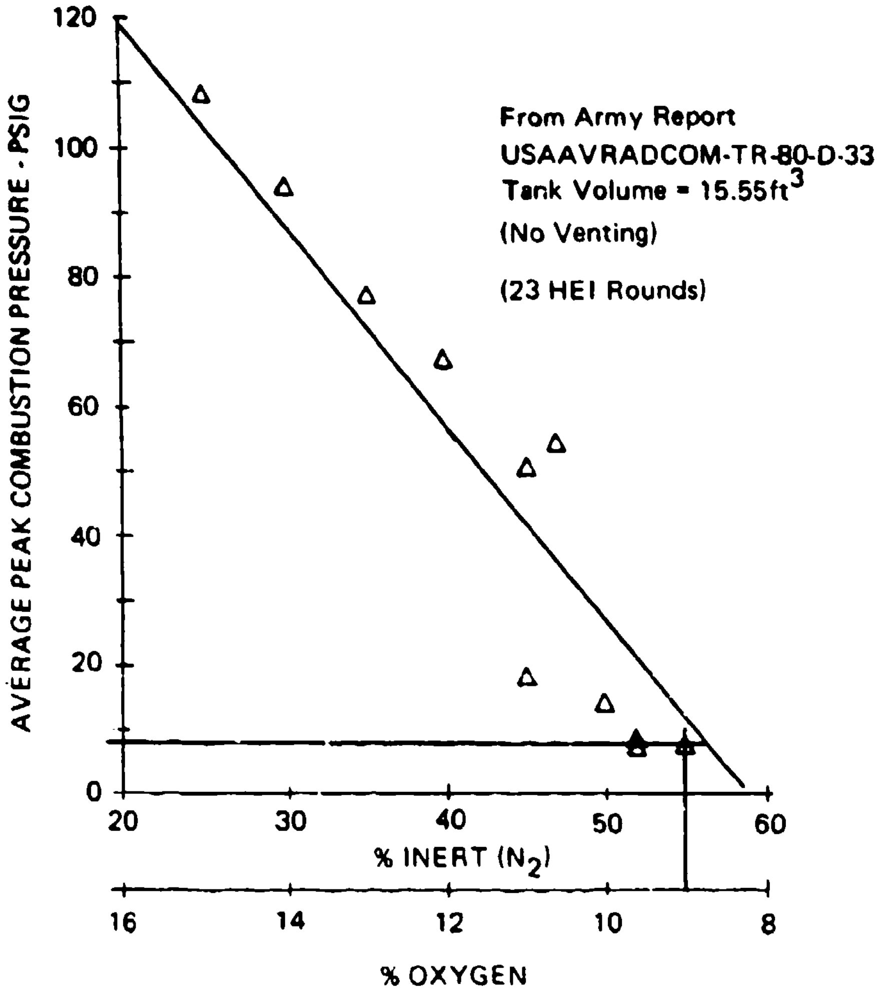


Figure 17. Peak Fuel Tank Combustion Overpressures for JP-4 and Air Mixtures

Maintaining an inert ullage during ground standby is another important consideration. During ground standby, thermal expansion of the fuel could cause most or all of the ullage gases to be discharged out through the vent system if the tanks were filled to the expansion space volumes. When the fuel cooled again, air would be drawn into the tanks through the dive valves, unless provision was made to repressurize the tanks with inert gas. With a stored gas system it would be relatively simple to maintain fuel tank inerting due to thermal cycles during ground standby. However, with a demand system the ground crew would have to periodically operate the OBIGGS using the APU or compressed air from an external source.

While the problems cited above complicate the inerting process, none of them produce unacceptable airplane penalties. The increased protection and potential payoff of 100% inerting justifies some minor added weight penalties and operational difficulties. Therefore the best choice OBIGGS will include full time (100%) inerting. While arguments can be made for exceeding the 9% oxygen limit in friendly territory because the combat threat is low, full time inerting has the additional benefit of protecting the airplane against natural hazards such as lightning and electrostatic discharges.

Air evolution from the fuel as a result of aerial refueling was expected to be negligible because the tanks in the tanker aircraft are vented to atmosphere. Therefore, fuel in equilibrium at the tanker fuel tank pressure would be undersaturated with oxygen when it was pumped into the wing tanks of the receiver airplane and pressurized.

4.3 Fuel Scrubbing and Ullage Washing

Significant quantities of oxygen may be carried into the airplane during refueling due to the solubility of air in fuel. During climb out the dissolved air tends to come out of solution due to the reduction of tank pressure. Therefore, if oxygen evolution from the fuel is not managed properly, even initially inert ullage could become hazardous during taxi or flight.

Controlled oxygen removal can be achieved by scrubbing the fuel using either climb scrubbing and/or aspiscrubbing. Climb scrubbing utilizes nozzles located in the bottom of the fuel tanks to create a multitude of small bubbles that liberate dissolved oxygen. The evolved gases then mix with ullage gases and the

resulting mixture is vented overboard as required to maintain proper tank pressures. Aspiscrubbing allows the fuel to be scrubbed on the ground during refueling by using the inert gas in the fuel tanks from the previous mission to scrub the fuel. The aspiscrub unit uses the motive flow of the incoming fuel to cause the fuel and ullage gases to mix in an aspirator, and separate in a swirl chamber. The evolved oxygen and other gases in the mixture are then expelled through the vent system.

Ullage washing is another technique that can be used to control ullage oxygen concentrations to safe levels. With ullage washing, the oxygen and other gases are allowed to evolve from the fuel, but nitrogen rich inert gas sweeping through the ullage prevents oxygen concentration from exceeding safe limits. Usually ullage washing requires higher inert gas flow rates than fuel scrubbing, but the ullage washing technique may result in a lighter and simpler system.

Fuel scrubbing and ullage washing techniques were evaluated individually and in combinations (hybrid systems). Although experimental confirmation is lacking, intuitive arguments were used to rule out aspiscrubbing by itself as a viable technique for fuel scrubbing. This conclusion is based on the following factors:

- o Results of tests using aspiscrubbing in conjunction with liquid nitrogen inerting (Ref. 3). With LN_2 inerting the ullage oxygen concentration at the end of the mission is about 1%. Ideally, the ullage oxygen concentration would remain at 1% during refueling but some contamination of the ullage gases by evolved gases occurs in practice. As a result the oxygen concentration increases to about 5% at the end of refueling. Since oxygen is more soluble than nitrogen in the fuel, the ullage oxygen concentration increases from about 5% to about 9% during airplane climbout. Since 9% is the safe limit, if the initial ullage concentration was greater than 1%, the final oxygen concentration can be expected to exceed 9%, unless additional scrubbing is performed. Since the initial ullage oxygen concentration with NEA inerting ranges from about 5% to 9%, the concentration at the end of climbout using aspiscrubbing may be expected to significantly exceed the 9% limit. (This conclusion may be debated, based on studies that indicate the maximum allowable oxygen concentration increases with altitude. However, the 9% concentration was assumed as the safe limit throughout the current study).

- Results of comparing aspiscrubbing and climb scrubbing using NEA for the C-5 airplane (Ref. 10). Calculations were made to determine the maximum allowable ullage gas oxygen concentration at the start of refueling using aspiscrubbing to prevent the ullage concentration from exceeding 9% at the end of climb. The results showed that the initial concentration must be 0.8% or less for safety; with an initial concentration of 5%, the 9% limit could be exceeded at about 12,000 feet.

- Aspiscrub nozzles tend to be relatively long to allow sufficient mixing between the fuel and the entrained ullage gases. Since short nozzles apparently have not been developed, aspiscrub nozzles for ATF or other fighter aircraft application would be located in fuselage tanks. This would significantly delay and complicate aircraft refueling.

Although aspiscrubbing by itself was not considered feasible, the case of a hybrid system combining aspiscrubbing with climb scrubbing was included in the trade-off studies. A total of seven cases were selected for fuel scrubbing/ullage washing trade-off (Figure 18). Case 1 was the baseline case in which scrub nozzles alone were used with 90% scrubbing efficiency, the measured efficiency of current climb scrub nozzles. Case 2 assumed ullage washing only from completion of refueling until the end of climbout. Case 3 was similar to Case 2 except the period for washing was a total of 5 minutes, 10 minutes on either side of take-off. Case 4 was similar to Case 1 except that the scrubbing efficiency was reduced from 90% to 25%. Calculations reveal that the ullage oxygen concentration will exceed the 9% safe level for some period of time, even with high scrub flow rates, if 90% efficient scrub nozzles are used. A nozzle with 25% efficiency eliminates the characteristic "overshoot" in ullage oxygen concentration during scrubbing. Developing a 25% efficient nozzle should not be too difficult; since efficiency is related to bubble size and residence time, reducing the efficiency probably can be achieved by simply increasing the bubble size. Case 5 was designated as aspiscrub only but was not sized because aspiscrub alone was not judged to be a viable concept as explained above. Case 6 combined aspiscrubbing and climb scrubbing. Case 7 combined aspiscrubbing and ullage washing. Although not tabulated, combined climb scrubbing with 90% efficient scrub nozzles and ullage washing was also examined. This technique did eliminate the oxygen concentration peaks due to high efficiency climb

scrubbing, but required about the same amount of inert gas as the inefficient scrub nozzle system. Since the latter is inherently less complex, further study of the combined climb scrub/ullage wash technique was abandoned. Results of the seven cases studied are summarized in Figure 18. Aspiscrub when combined with either climb scrubbing or ullage washing had lower inert gas storage and generation requirements than the baseline (Case 1). However, when all the components were considered the overall system weight was greater than the baseline. Ullage washing to the end of climbout was not acceptable because the ullage oxygen concentration exceeded 9% after ullage washing was discontinued. The best ullage washing technique was to wash 5 minutes before and after take-off. Washing 5 minutes before take-off ensured that the ullage was inert at take-off. Since the climbout requires only about 3 minutes, the ullage washing for 5 minutes after take off prevented the oxygen concentration from exceeding 9% in cruise. The best choice was the inefficient climb scrub technique (Case 4). This system provided 100% inerting with only a modest weight increase and offered the simplicity of a single system compared with a hybrid system.

4.4 OBIGGS Integration

Using an environmental control system (ECS) and the associated cooling equipment to condition engine bleed air to desired temperatures and pressures is mature technology. The same type of ECS equipment is appropriate for conditioning supply air for an OBIGGS. The quality of the bleed air in terms of dirt and moisture content can be controlled by a centrifugal separator. The pressure of the bleed air was sufficient to operate the OBIGGS, except at low engine power settings (low bleed air pressures) where a boost compressor was a better trade than increasing the size of the air separator module to produce the required inert gas flow rates. An additional heat exchanger was required to cool the bleed air to acceptable OBIGGS supply air temperatures. The bleed air flow rates available in an ATF engine were sufficient for all OBIGGS operations. The primary power requirements for a stored gas OBIGGS were for operating the high pressure compressor. A hydraulic motor would require significantly less power than an electric motor but hydraulic power could not be used in the bay where the OBIGGS would be installed. The electrical power required was about 14.5 kilowatts which was a significant but manageable additional electrical load. The principal power requirement for a demand system was the power to operate the boost compressor. This requirement was about 10.4 horsepower. Key system requirements are summarized in Table 6.

- CASES
  - CASE 1 BASELINE (90% EFFICIENT)
  - CASE 2 ULLAGE WASH TO END OF CLIMBOUT
  - CASE 3 ULLAGE WASH 5 MINUTES BEFORE AND AFTER TAKEOFF
  - CASE 4 25% EFFICIENT CLIMB SCRUB ONLY (21% OXYGEN INITIAL ULLAGE)
  - CASE 5 ASPISCRUB ONLY
  - CASE 6 ASPISCRUB/CLIMB SCRUB
  - CASE 7 ASPISCRUB/ULLAGE WASH
- RESULTS

CASE	Δ SCRUB GAS REQUIREMENT (LB)	Δ STORAGE REQUIREMENT (LB)	Δ IGG GENERATION RATE (LB/MIN)	BASELINE Δ WEIGHT (LB)
CASE 1	0	0	0	---
CASE 2	*	---	---	---
CASE 3	11	12	.10	+19
CASE 4	6	6	.04	+9
CASE 5	*	---	---	---
CASE 6	−7	−7	−.08	** +10
CASE 7	−5	−5	−.05	** +11

* DID NOT INERT ULLAGE

** INCLUDES WEIGHT OF ASPISCRUB UNIT

Figure 18. Weight Trade-off Study for Fuel Scrubbing Techniques

TABLE 6. KEY SYSTEM REQUIREMENTS FOR OBIGGS INSTALLATION

OBIGGS SYSTEMS REQUIREMENTS

- Stored Gas System
  - Design IGG supply temperature $\leq 100^{o}$ F
  - IGG supply flow: 5 lb/min
  - Desired IGG supply pressure: $\geq$ 60 psig
  - Electrical: 14.5 KW
  - HP Compressor (either electrical or hydraulic)
    - Electrical: 14 HP
    - Hydraulic: 14 HP
  - Pneumatic: none
  - Bleed air: 20 lb/min

- On-Demand System
  - Design IGG supply temperature $\leq 100^{o}$ F
  - IGG supply flow: $\leq$ 50 lb/min
  - Design IGG supply pressure: $\geq$ 60 psig
  - Electrical: 7.8 KW
  - Hydraulic: none
  - Pneumatic: none
  - Bleed air: $\leq$ 200 lb/min

The stored gas OBIGGS is not expected to impact engine life since extracting bleed air is common practice. However, the on and off cycling of the bleed air requirements for the demand system may adversely affect the engine control systems and engine life. The ECS requirements for the OBIGGS were quite small relative to the total ECS requirements for the ATF airplane and the additional heat sink required for cooling OBIGGS supply air would not impact the ATF design. The fuel penalty for supplying bleed air for the design mission was about 34 pounds. No adverse impact on other ATF aircraft subsystems was anticipated as result of installing an OBIGGS.

4.5 Airplane Ground Standby

Military airplanes are commonly refueled soon after landing for round standby for the next mission. Projections of utilization rates were established for both peace time and war time operations (Figure 19). In peace time, a 5 day week would pertain. During each day there would be a 16 hour flight window, an average of 1.1 sorties per day and an average sortie flight time of 1.5 hours. In war time operations would be 7 day per week, 2 shifts per day utilization. The sortie rate would be about twice that of current aircraft and the average sortie flight time would be about 2 hours. Again a 16 hour flight window would be used but a 15 minute airplane turnaround time would be imposed in war time. The maximum ground standby time for all operations would be 48 hours. Therefore, the optimal OBIGGS design was based on a fully fueled airplane with a 48 hour ground standby requirement.

Gray and Shayeson (Ref. 11) recorded ground and in-flight fuel temperatures for several fighter and larger aircraft. Their results revealed that temperature variations approaching 60° F are possible due to diurnal cycles. Since jet fuels expand at the rate of about 1% for each 20° F change in temperature and military airplanes use a 3% expansion space, a change of 60° F could expel all the ullage gases out through the vent system. To replace ullage gases as the fuel cooled again would take about one pound of NEA at the lowest temperatures likely to be encountered. Therefore, about two pounds of make-up NEA would be required for a 48 hour ground standby.

4.6 Benefits and Risks of Weight Reduction Schemes

Previous studies have revealed that relaxing the 9% ullage concentration limit could significantly reduce the OBIGGS weight and airplane penalties. Specific weight reduction schemes were investigated in this program and the important results are summarized in this section.

4.6.1 Effect of Increasing Maximum Ullage Oxygen Concentration to 12%

Studies were made to determine if an ullage oxygen concentration of 12% by volume was acceptable for emergency descents, final descents into home

PEACE TIME

- 5 day week
- Sortie generation rate is 1.1 per day
- Sortie length is 1.5 flight hour
- 16 hour fly window

WAR TIME

- 7 day week - 2 shifts
- Sortie generation rate - classified (approx. twice today's aircraft)
- Sortie length is 2 flight hour
- 16 hour flight window
- 15 minute turnaround

48 hour is maximum ground stand-by time

Figure 19. Projected ATF Utilization Rates

base, or continuous usage under all threats. This was done by conducting a benefit and risk trade-off using a baseline ATF stored gas OBIGGS. Allowing the oxygen concentration to increase to 12% during an emergency descent would reduce the system weight by about 27 pounds or 10% of the total when compared to the OBIGGS sized for the emergency. Allowing the oxygen concentration to increase to 12% during final descent would reduce the weight by about 58 pounds or 20% of the total weight. The weight savings are greater for the final descent case than for emergency descent because of the greater ullage volume at the end of the final descent. Obviously, minimizing aircraft weight is a primary goal in any design especially for fighter aircraft and the weight savings due to relaxing the 9% limit are attractive. However, the evidence from the test results such as those shown in Figure 17 suggests that a 12% oxygen concentration would probably not prevent explosive overpressures. Furthermore, with multiple ignition sources such as accompany an HEI round, higher overpressures are possible. After considering the merits and disadvantages of relaxing the 9% oxygen concentration limit, the benefits of full time protection against both combat and natural hazards were judged to outweigh the risks associated with reduced weight systems. Therefore, the best choice fighter OBIGGS preliminary design was based on the 9% limit.

4.6.2 Effect of NEA Quality on System Sizing

The issue of NEA quality must be addressed separately for the stored gas and the demand OBIGGS. For a stored gas system NEA quality requirements for fuel scrubbing are the dominant considerations. If fuel scrubbing was not required, only tank repressurization would be necessary and a NEA quality approaching 9% would be the best choice. However, NEA qualities near 9% are not well suited for fuel scrubbing because large amounts of scrub gas would be required. Previous studies, e.g., Ref. 10, revealed that a NEA quality of 5% is close to optimal. In this study NEA_4 and NEA_7 were compared with NEA_5 in a trade-off study. The trade-off involved two primary factors: (1) The quantity of inert gas required for scrubbing decreased as the oxygen concentration in the scrub gas decreased. (2) The weight of the OBIGGS increased for a given NEA flow rate as the oxygen concentration decreased. The system weight would increase by about 7 pounds for NEA_4 and 1 pound for NEA_7, confirming that a quality of 5% is the best choice for a stored gas system.

For a demand OBIGGS, NEA quality is not a factor in trade-off studies. The OBIGGS must be sufficiently large to limit the oxygen concentration to 9% during maximum descent rates but no larger.

4.6.3 Allowing the Dive Valve to Open During Emergency and Final Descents

Allowing the dive valve to open during emergency and final descents offered a potentially significant weight saving for a stored gas OBIGGS. Since the NEA quality of the stored gas was about 5%, some air could enter the fuel tanks through the dive valve and still prevent the ullage oxygen concentration from exceeding 9%. Calculations revealed that the system weight could be reduced by 38 pounds or 35 pounds if air was allowed to enter during an emergency descent or final descent respectively. The disadvantage of allowing air to enter was that the air and inert gases may not mix uniformly. Potential hazards associated with pockets of air in otherwise inert tanks are not well understood, but allowing air to enter was not considered a good trade-off.

Since a demand OBIGGS would not have a safety margin with respect to ullage oxygen concentrations, the dive valve must remain closed to preserve a safe ullage for a demand OBIGGS.

4.6.4 Full-Time versus Part-Time Fuel Tank Protection

A comparison was made between using the OBIGGS for full time and part time fuel tank fire protection. In this context part time protection was defined as protection that was limited to situations when hazardous exposures could be predicted, such as prior to entering a combat zone. In this operating mode the OBIGGS would be activated about 5 minutes prior to entering a hazardous zone and ullage washing would begin. Ullage washing would continue for 10 minutes to inert the ullage. Additional inert gas for tank repressurization would be supplied as required. Based on the design mission and a stored gas OBIGGS, part time inerting with an OBIGGS would resulted in a weight saving of about 31 pounds. While significant, this weight savings was not sufiicient to offset the increased aircraft vulnerability associated with part time inerting.

4.6.5 Use of Halon 1301 for Maximum Rate Descents

Since maximum rate descents are relatively infrequent events, sizing a demand OBIGGS for high speed descents may lead to an unnecessarily large system. (The stored gas system sizing was not an issue since the only consequence would have been slightly larger line sizes). An alternative is to utilize a hybrid system consisting of a smaller OBIGGS and Halon bottles that would discharge only if a maximum rate descent occurred. Since the Halon bottles would only have to be serviced after a maximum rate descent, additional logistics problems would be minimal. Using Halon reduced the weight of the demand OBIGGS by about 56 pounds but the weight was still higher than the stored gas OBIGGS.

4.7 Design Considerations

4.7.1 Hot and Cold Day Effects

OBIGGS requirements for Military hot, cold and standard days were calculated to find the most severe and thus the sizing condition. The results are summarized in Figure 20. Obviously, as the temperature decreases the mass required for repressurization increases by the ideal gas law. Since the performance of the air separation modules is degraded at higher temperatures, one might suspect that hot day operation may still be the sizing condition. The mitigating factor here is the performance of the ECS equipment. Even though the bleed air temperature may vary by 100° F or so, the supply air temperature to the OBIGGS after processing by the ECS is nearly independent of the bleed air temperature. However, hot day conditions do dictate the sizing of the ECS and ECS sizing was not subject to trade-off studies because the supply air temperature had to be cooled sufficiently to prevent thermal damage to the air separation module. In summary, then, the ECS must be designed for hot day operation, but the supply air temperature to the OBIGGS is essentially independent of the type of day. Therefore, the OBIGGS was sized for a cold day.

4.7.2 Effect of Taxi Time

The baseline mission included a 15 minute taxi time. With conventional high efficiency scrub nozzles, the ullage oxygen concentration would exceed the safe limit for a short time but would return to the safe limit prior to

DAY TYPE	TOTAL MISSION REQUIREMENTS (LB)	STORAGE REQUIREMENT (LB)	IGG GENERATION RATE	Δ WEIGHT (LB)
COLD	54	41	.67	BASELINE
STANDARD	45	33	.53	≃ −20 (NOT COMPUTED)
HOT	40	30	.48	−34

RESULTS BASED ON ECS DESIGNED TO PROVIDE 95°F SUPPLY AIR FOR ANY ATMOSPHERIC TEMPERATURE CONDITION

Figure 20. Effect of Atmospheric Temperature on OBIGGS Sizing

takeoff. However, on ground alert status or for war time hot turn around the taxi time would be reduced to about 2 minutes. If scrubbing was initiated 2 minutes prior to take-off, the ullage oxygen concentration would exceed 9% during climbout. Remedies were developed to ensure that the ullage remained inert at all times. For airplanes on an alert status, the fuel was scrubbed for 13 minutes (ground scrubbed) prior to designating the airplane ready for alert status. Then, the fuel was scrubbed in the usual manner for the 2 minutes of taxi and during climb. On a war time hot turn around mission about 12 minutes were available for fuel scrubbing. The most favorable technique found was to start scrubbing when the tanks were about half full and continue scrubbing through the climbout. In both of these techniques a scrub nozzle with a 25% efficiency provided full time inerting both on the ground and during climbout. The stored gas OBIGGS designed for full time protection for all taxi times was found to require an inert gas generation rate of 0.65 pound per minute and a storage capacity of 50 pounds of NEA_5. Since these requirements represented only a modest increase in OBIGGS size and weight, the best choice stored gas OBIGGS was based on these requirements.

4.7.3 Effect of Fuel Type

The three fuels commonly used for military airplanes, i.e., JP-4, JP-5 and JP-8 were considered. Although similar in many respects, JP-4 fuel was used for OBIGGS design studies because oxygen is more soluble in JP-4 than in the other fuels. The results of the scrubbing and other mission requirements revealed that an OBIGGS designed for JP-4 would be about 8 pounds heavier than one designed for JP-5 or JP-8 (Figure 21). The effect of preventing JP-4 fuel boiling on climb valve and demand regulator settings is discussed elsewhere in this report.

4.7.4 Effect of Fuel Temperature Variations

The fuel temperature in an ATF airplane could range from about -50° F to more than 140° F. The high temperatures result from using the fuel as a heat sink for aerodynamic heating and cooling on-board equipment during supersonic flight. Fuel temperature variations were included in all the OBIGGS sizing analyses. The temperature solution routine includes film coefficients for aerodynamic heating or cooling, the thermal resistance of

FUEL TYPE	SCRUB REQUIREMENT (LB)	MISSION REQUIREMENT (LB)	BASELINE ΔWEIGHT (LB)
JP4	14	64	BASELINE
JP5	10	55	−8
JP8	10	55	−8

NOTE: DISSOLVED OXYGEN JP4 > JP5 ≥ JP8

Figure 21. Effect of Fuel Type on OBIGGS Sizing

the tank wall, the change in wetted area as fuel is depleted and a factor to estimate the effect of natural convection on bulk fuel temperatures.

Typically, one would expect fuel temperatures and outside air temperatures to follow similar trends. Furthermore, since inert gas production improves at lower temperatures for most ASM's, the effect of fuel temperature on inert gas production could be somewhat self-compensating. (Low fuel temperatures increase inert gas requirements but inert gas production could also increase somewhat proportionately due to lower supply air temperatures). However, in this study the ECS was designed to provide a constant supply air temperature for all flight conditions. Therefore, inert gas requirements increased as the fuel temperatures decreased.

4.7.5 Effect of Climb Valve Setting on OBIGGS Size and Weight

The weight and volume of the OBIGGS are strong functions of the climb valve setting. The higher the climb valve setting, the more the tanks are pre-pressurized prior to descent which translates into lower requirements for tank repressurization by the OBIGGS. In practice, the climb valve setting is bounded by the pressure requirements to prevent fuel boiling and the additional structural weight that accompanies higher pressure tanks.

In this study, a maximum fuel temperature of 145° F was assumed. since the average vapor pressure of JP-4 fuel is about 6 psia at 145° F, the pressurization schedule patterned after the schedule for the F-16 airplane (Figure 22) was appropriate for this study.

For the stored gas OBIGGS, the F-16 normal mode pressurization schedule was selected as the baseline. For comparison purposes the F-16 combat mode pressurization schedule and a variable demand regulator with a constant 6.4 psig climb valve setting were used. During descents the variable demand regulator maintained the tank pressure at 1 psig or 6.5 psia whichever was greater. The range of tank pressures with the variable demand regulator is shown in Figure 23. Results of the comparison studies (Figure 24) revealed that the variable demand regulator with the constant 6.4 psig climb valve resulted in a significant saving of inert gas for the stored gas OBIGGS.

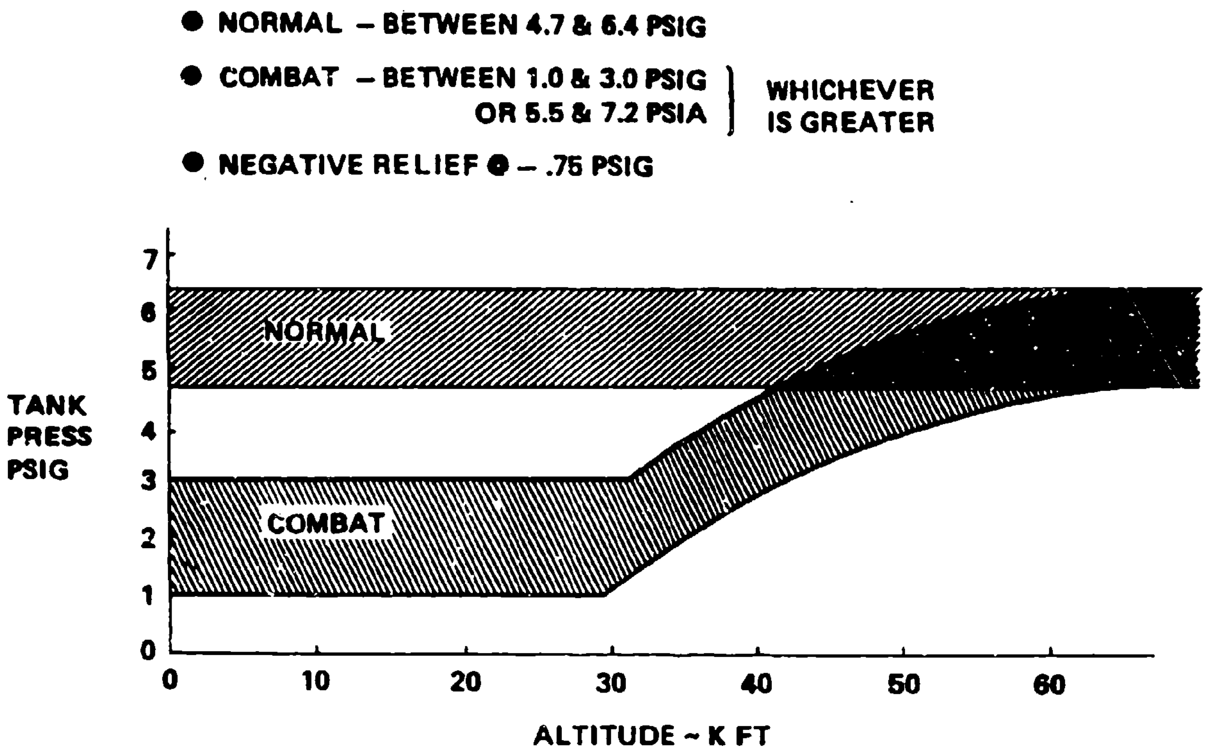


Figure 22. F-16 Fuel Tank Pressurization Schedule

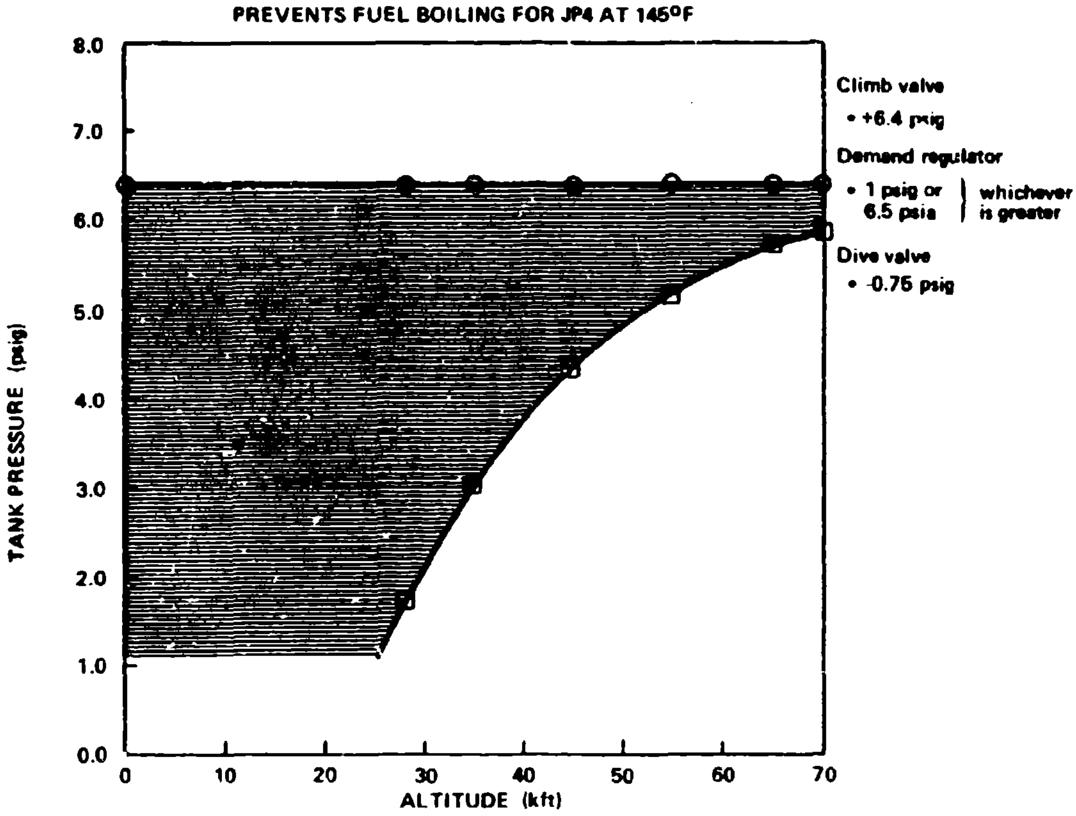


Figure 23. Pressurization Schedule for Best Choice Stored Gas OBIGGS

- REPRESSURIZATION SCHEDULES
  - BASELINE
    - F-16 NORMAL MODE
  - CASE 1
    - F-16 COMBAT MODE
  - CASE 2
    - F-16 NORMAL MODE CLIMB VALVE
    - F-16 COMBAT MODE DEMAND REGULATOR (VARIABLE)

REPRESS – URIZATION SCHEDULE	REQUIREMENTS			Δ IGG GENERATION RATE (LB/MIN)	BASELINE Δ WEIGHT (LB)
	ΔSCRUB (LB)	Δ STORAGE (LB)	Δ MISSION (LB)		
BASELINE	---	---	---	---	---
CASE 1	+2	–5	–14	–.14	–20
CASE 2	0	–7	–19	–.18	–26

Figure 24. Effect of Pressurization Schedule on System Sizing

For the demand OBIGGS, the climb valve setting was also set at 6.4 psig, but the demand regulator was set at a constant 6.0 psig. The dive setting was reduced to -1.0 psig. During descent the pressure was allowed to decrease from the demand regulator setting to the dive valve setting to minimize the size of the demand OBIGGS. On this basis an OBIGGS which produced a peak flow rate of 22 pounds per minute of NEA_{12} was required.

4.7.6 Effect of Partial Fuel Loading

Fighter aircraft are commonly fueled to the expansion space volume prior to a mission because they are usually volume rather than weight limited. However, since shortened missions with partial fuel loading are also flown, the impact on OBIGGS sizing of a typical mission with partial fuel loading was evaluated. A 74 minute mission with a total fuel loading of 17,130 pounds (compared to 19,345 pounds for the design mission) was selected. Two factors combined to increase the OBIGGS size and weight for the shortened mission. First, the reduction in mission time reduced the time available for generating inert gas in a stored gas system. Second, the partial loading created a larger ullage volume and increased inert gas requirements for repressurization during the mission. The overall effect increased the system weight by 35 pounds (Figure 25). Since a mission with partial fuel loading was judged to be an unusual case, the penalty to inert a partially fueled airplane was not included in the final design.

4.8 Comparison of OBIGGS with Other Protection Systems

Since Halon, LN_2 and foam fuel tank fire protection systems are implemented on current military aircraft, it was of interest to compare these systems with the OBIGGS for ATF application. The results of this comparison are summarized in Figure 26. Clearly, the LN_2 and Halon systems are the most attractive in terms of weight and volume penalties and simplicity. However, both of these present fundamental logistics problems which are probably unacceptable in the forward operating locations from which the ATF's could operate. In addition, the cost of continually replenishing Halon bottles for full time inerting would probably be prohibitive. In addition to a large weight penalty, the foam may not be compatible with the fuel tank temperature environment in supersonic flight. Development of a high temperature foam could solve that problem. However, when all factors are considered, the OBIGGS was the best overall system for ATF fuel tank fire protection.

ASSUMPTIONS

- SHORTEN OBIGGS DESIGN MISSION CRUISE
  OUT AND BACK BY 1/2 TO MISSION TIME OF 74 MINUTES
- DECREASED FUEL LOADING CORRESPONDING TO SHORTER CRUISE TIME FROM 19345 LB TO 17130 LB

CASE	MISSION REQUIREMENT (LB)	STORAGE REQUIREMENT (LB)	IGG GENERATION (LB/MIN)	Δ WEIGHT (LB)
BASELINE	54	41	.67	--
SHORT MISSION	55	74	.98	+35

Figure 25. Effect of Partial Fuel Loading on OBIGGS Sizing

ASSUMPTIONS	STORED GAS		DEMAND		DEMAND & EMERG. HALON		HALON 1301		LN_2		FOAM	
	• Optimal System • Advanced ASM • 0.65 lb/min NEA_5 w/boost compressor		• Current system • Advanced ASM • 22 lb/min NEA_{12}		Current system Advanced ASM 15 lb/min NEA_{12} w/boost compressor		• Fuel time prot. • One mission supply • 20% by volume repress. flow • Fuel absorbtion 0.8 Lb/Min		• One mission supply • Same mass rqmt. as OBIGGS stored gas system		• Fine pore • 50% void	
	Weight	Volume	Weight	Volume	Weight	Volume	Weight	Volume	Weight	Volume	Weight	Volume
System Components												
• Bleed air supply	5 lb	0.1 ft3	90 lb	2.0	64 lb	1.8 ft3	0	0	0	0	0	
• ECS (Δ)	7	0.1	55	1.6	41	1.5	0	0	90 (HX)	0	0	
• IGG supply air conditioning	6	0.4	35	0.9	21	0.8	2	0.1	0	0		
• Compressor, motor, intercoolers	83	2.5	0	0	30	0.2	0	0	0	0	0	
• Storage bottle & fittings	80	3.7	0	0	20	0.2	42	1.2	54	1.6	0	
• IGG	14	0.4	143	3.4	64	1.8	0	0	0	0	0	
Distribution system	38	0.2	42	0.2	39	0.2	17	0.1	12	0.1	0	
NEA, halon, LN2, or foam	25	0	0	0	30	0	107	0	77	0	282	
Retained fuel	0	0	0	0	0	0	0	0	0	0	452	
Total	258 lb	7.4 ft3	365 lb	8.1 ft3	309 lb	6.3 ft3	168 lb	1.4 ft3	233 lb	1.7 ft3	734 lb	NA

Figure 26. Comparison of OBIGGS with Other Protection Systems

4.9 Best Choice ATF OBIGGS

Even after completing all the trade-off studies discussed above, a clear choice between the stored gas and demand OBIGGS application for ATF application did not emerge. This was primarily because the advantage of the lower weight of the stored gas OBIGGS was somewhat offset by the predicted higher maintenance costs and reliability problems of the stored gas OBIGGS. Since the demand OBIGGS requires only air separation modules and a flow control device, the system is nearly passive. However, the requirement to size the demand OBIGGS for the peak flow rate in the mission caused the ASM and ECS equipment to be relatively heavy. Little can be done about the weight of the ASM since it has to be sized for the highest flow rate required. However, since about half the weight of the demand OBIGGS was due to the ECS and related equipment (such as the precooler, other heat exchangers and ducting) required to condition the supply air at maximum flow rates, unconventional techniques could reduce the ECS weight substantially. For example, using an expendable material such as water for cooling the high flow rates offers the potential for considerable weight savings. This is because the time interval in which very high flow rates are required is measured in seconds. As such, the supply air conditioning process could be significantly downsized and still perform very satisfactorily for the rest of the mission. Although expendibles complicate the system, the weight reduction payoff could justify their use. Another way of reducing the weight penalty of the demand system would be to develop fibers for air separation modules that would perform satisfactorily at high temperatures. For example, if a supply air temperature of 160° F was acceptable for ATF application, the weight of the ECS itself could be significantly reduced by about 90%.

Another key issue for the demand OBIGGS is the effect of transient supply air flow rates on ASM performance. Tests should be conducted to investigate these transients and address any unforeseen problems. Once the areas of uncertainity are addressed and the system weight optimized, the demand OBIGGS may emerge as the best choice OBIGGS for fighter aircraft.

At this juncture, the stored gas OBIGGS was the best choice OBIGGS for fighter aircraft, primarily because of its lower weight and the sensitivity factor that translated into 3 pounds of additional fuel weight for each pound of additional

equipment weight. This best choice OBIGGS was sized based on mission requirements and optimized by trade-off studies. The key trade-off studies for sizing were the requirement for a fast turn around and the fuel tank pressurization schedule. The best choice OBIGGS required an ASM sized to produce 0.65 pounds per minute of NEA_5 and 50 pound of inert gas storage.

5.0 CONCLUSIONS AND RECOMMENDATIONS

An OBIGGS is feasible for fuel tank inerting on the ATF and other fighter aircraft. NEA inerting provides full time protection against fuel tank explosions for both natural hazards and combat threats up to 23 mm HEI by maintaining the oxygen concentration in the fuel tank ullage below 9%. Since the OBIGGS is supplied by engine bleed air, special ground handling equipment is not required and logistics problems are minimized.

The design of a stored gas OBIGGS was based on a constant inert gas production rate and an inert gas storage system. Analysis of various missons showed that the climb scrub requirement was 14 pounds on a cold day; the largest repressurization requirement was 56 pounds for an air-to-air combat escort mission for a cold day and assuming an emergency descent at any point in the mission. Climb scrubbing the fuel during taxi inerted the ullage by the initial climbout. Providing NEA_5 for all the repressurization requirements kept the ullage inert thereafter. A stored gas OBIGGS to meet these mission requirements (including 2 pounds for 48-hour ground standby) must generate an average of 0.65 pound per minute of NEA_5 and store 50 pounds of NEA.

The demand OBIGGS was sized to provide tank repressurization for the maximum descent profile of the airplane. This descent profile included a maximum "G" pullout in 10,000 feet to level out to sea level at Mach 1.2. The maximum repressurization rate was determined to be 77 pounds per minute at 7200 feet altitude, assuming a constant gauge pressure of 6.0 psig was maintained in the tank. By allowing the tank gauge pressure to drop to the dive valve setting of -1.0 psig, the repressurization flow rate was reduced to 22 pounds per minute and was the demand OBIGGS sizing criterion.

The mission analysis assumed a "well stirred" ullage of homogeneous composition and all the fuel tanks were modeled as one large tank. This may not apply to a fuel system where each tank does not have separate vent lines to the vent box and/or where the NEA cannot be distributed directly to each tank. Tests should be conducted to determine if the well stirred assumption applies when a number of tanks and more complicated vent systems are used. Weights and volumes of current technology permeable membranes, current technology molecular sieves and advanced technology permeable

membranes ASM's were evaluated. The advanced technology permeable membrane ASM was selected as the baseline for all fighter aircraft OBIGGS design and trade-off studies because:

- o volume and weight reductions of a factor of 10 to 20 were obtainable
- o the advanced ASM was the only feasible ASM for a demand OBIGGS.

Note that the weight and volume reductions in the overall OBIGGS was much less dramatic because the weight and volume of the ECS and other supporting equipment remained constant.

Preliminary designs were completed for both the stored gas and demand OBIGGS for the ATF airplane. The designs were optimized based on a large number of trade-off studies. Advanced technology ASM's allowed the demand OBIGGS to be contained within the packaging envelope available in the ATF airplane. Creative solutions were used to ensure full time inerting during the critical periods of fuel scrubbing and descent repressurizations as well as the rest of the mission and during ground standby. The total system weight of the optimized stored gas OBIGGS was 258 pounds and the volume was 7.4 cubic feet. The demand OBIGGS weighed 365 pounds and had a volume of 8.1 cubic feet. With the addition of a Halon system for protection during high speed descents the weight and volume of a demand OBIGGS could be reduced to 309 pounds and 6.3 cubic feet respectively.

The stored gas OBIGGS was the best choice based on these results. However, the demand OBIGGS had the advantages of simplicity and projected lower life cycle costs. Since about half the weight of the demand OBIGGS was for ECS equipment, techniques should be pursued to minimize the ECS penalty. If such progress is made, the demand system may emerge as the best choice OBIGGS.

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LIST OF ABBREVIATIONS AND ACRONYMS

AFTTA	Airplane Fuel Tank Thermal Analysis
ASM	Air Separation Module
APU	Auxiliary Power Unit
ATF	Advanced Tactical Fighter
BMAC	Boeing Military Airplane Company
ECS	Environmental Control System
FTIMA	Fuel Tank Inerting Mission Analysis
IGG	Inert Gas Generator
LCC	Life Cycle Costs
LN_2	Liquid Nitrogen
LRU	Line Replaceable Unit
LSC	Logistics Support Cost
LUCID	Life Utilization Criteria Identification in Design
MSIGG	Molecular Sieve Inert Gas Generator
NEA_x	Nitrogen Enriched Air (x = volume % O_2)
OBIGGS	Onboard Inert Gas Generation System
PATS	Propulsion Assessment for Tactical Systems
PMIGG	Permeable Membrane Inert Gas Generator

PSA Pressure Swing Adsorption

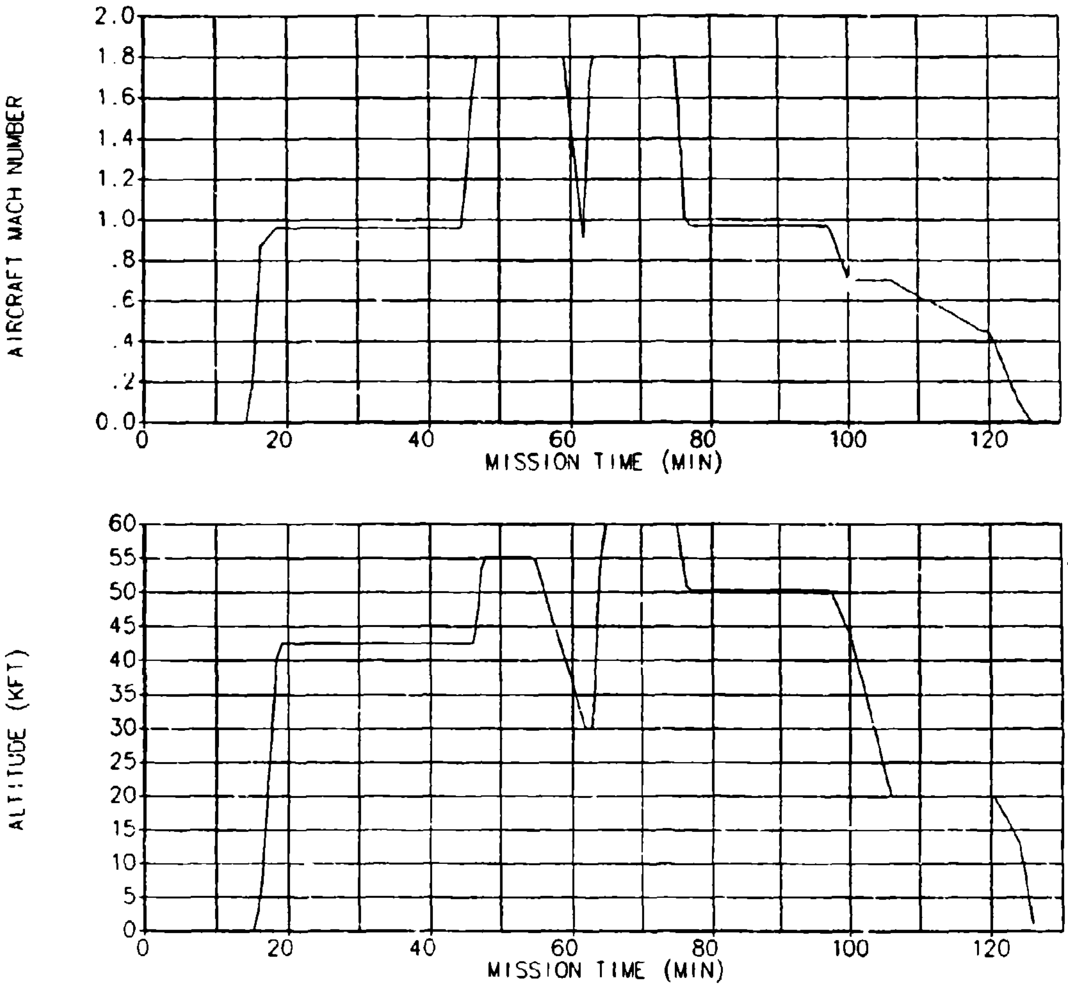
SAFTE Simulated Aircraft Fuel Tank Environment

TMS Thermal Management System

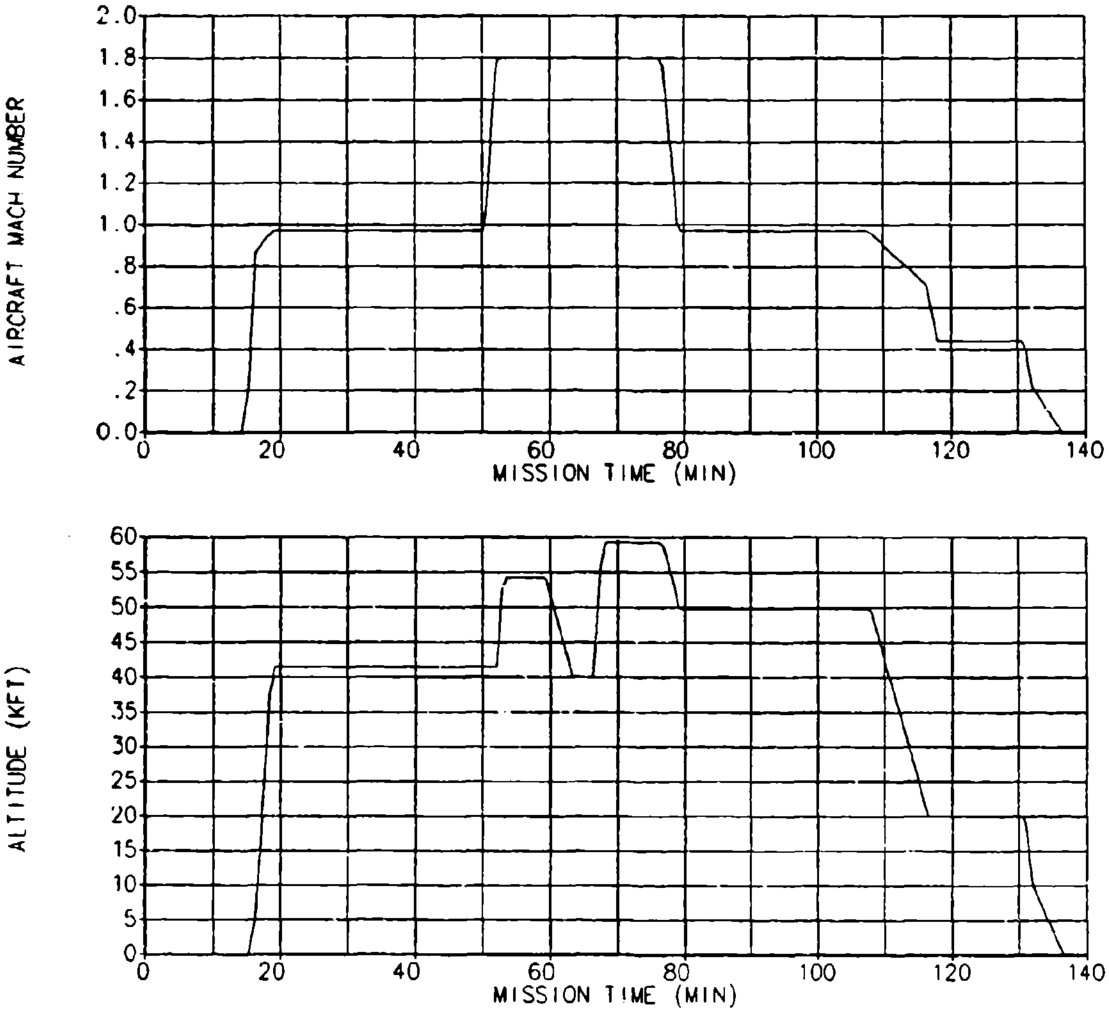
WPAFB Wright-Patterson Air Force Base, Dayton, Ohio

APPENDIX A - Mission Profiles

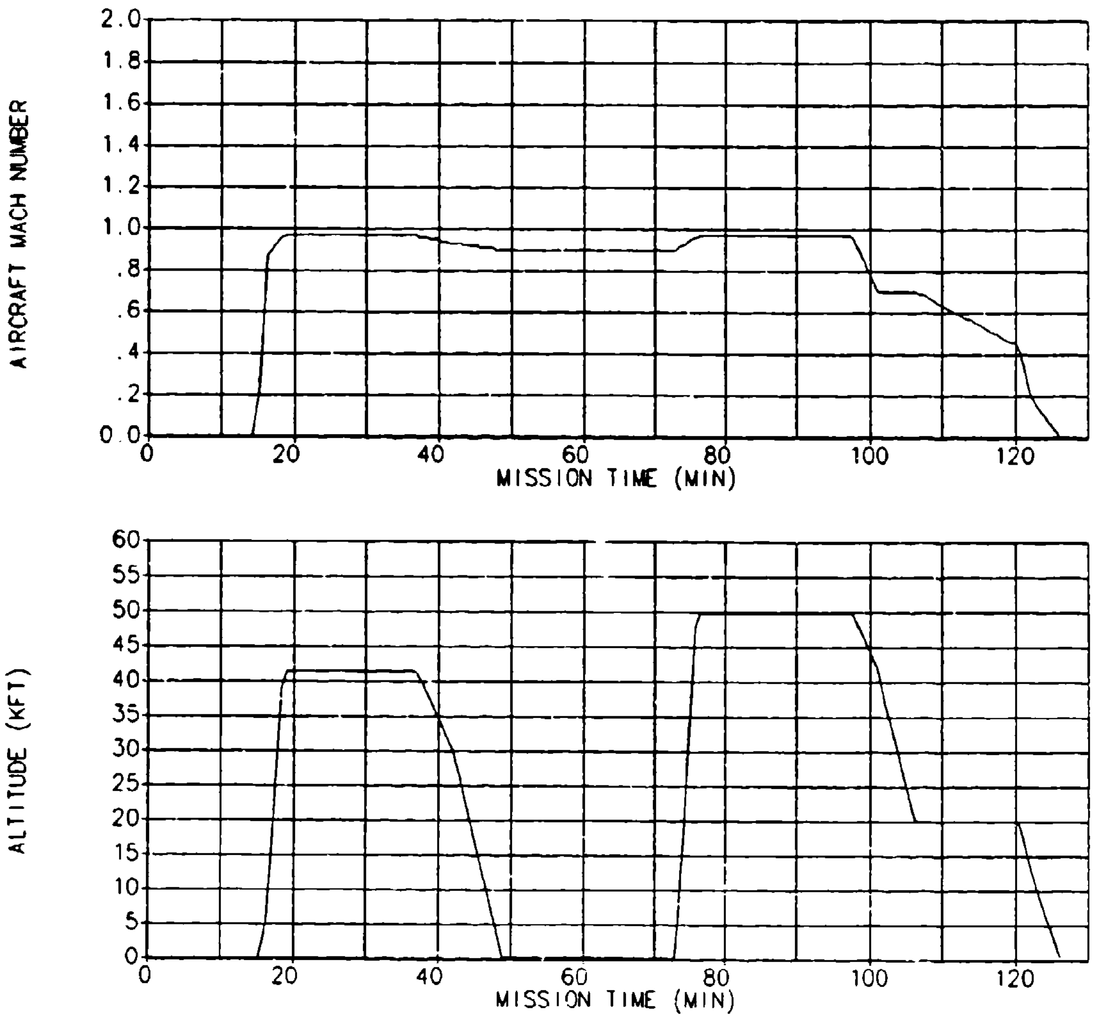
The missions shown correspond to the same order presented on Table 1 in Section 3.1. The first three missions were compiled from Propulsion Assessment Tactical Systems (PATS) study. The next eight were compiled from the Life Utilization Criteria Identification in Design (LUCID) study. The final mission was compiled from a BMAC computer code called "Advanced Air-to-Air System Performance Evaluation Model."



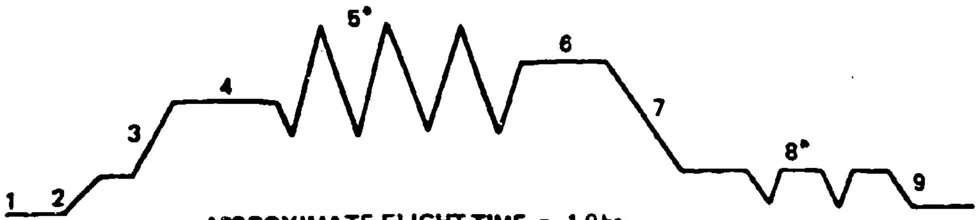
A-1. PATS Mission 1: Air-to-Air Combat



A-2. PATS Mission 2: High Altitude Air-to-Ground



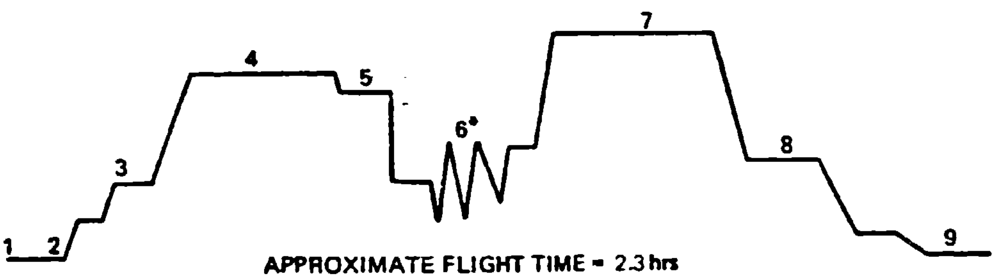
A-3. PATS Mission 3: Low Altitude Air-to-Ground



APPROXIMATE FLIGHT TIME = 1.0 hr

	SEGMENT	ALTITUDE (ft x 1,000)	MACH NUMBER	DISTANCE (nmi)
1	WARMUP/TAXI	0		
2	TAKEOFF	0.0 - 0.2	0.3	
3	SEGMENT CLIMB	0.2 - 8.0	0.5	
4	FORMATION CRUISE	8	0.5	25
5*	SUBSONIC WEAPON DELIVERY	3 - 15	0.7 - 0.4	
6	FORMATION CRUISE	12	0.5	25
7	DESCENT	12.0 - 0.1	0.69-0.45	
8*	TOUCH & GOs	0.1 - 0.0	0.25	
9	LANDING	0		

a. *Initial*



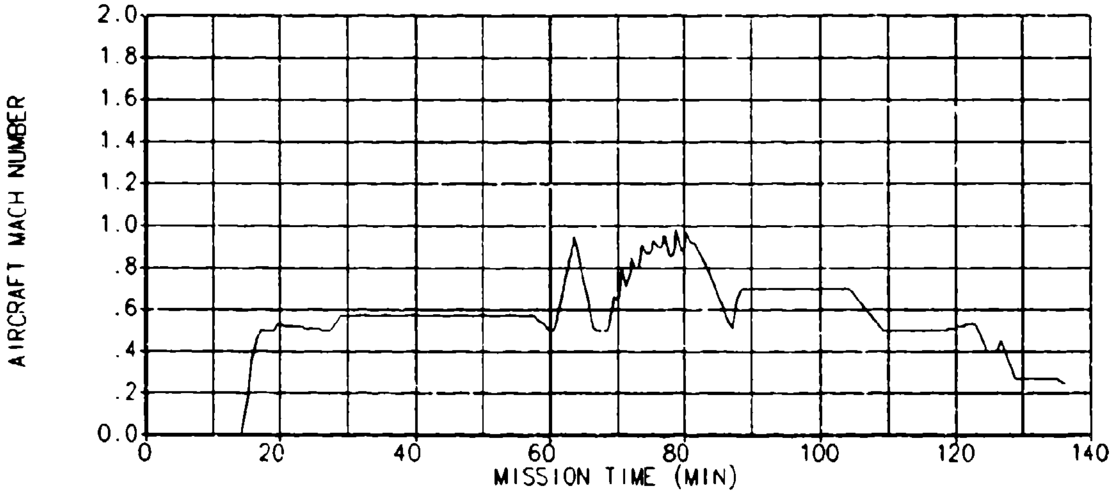
APPROXIMATE FLIGHT TIME = 2.3 hrs

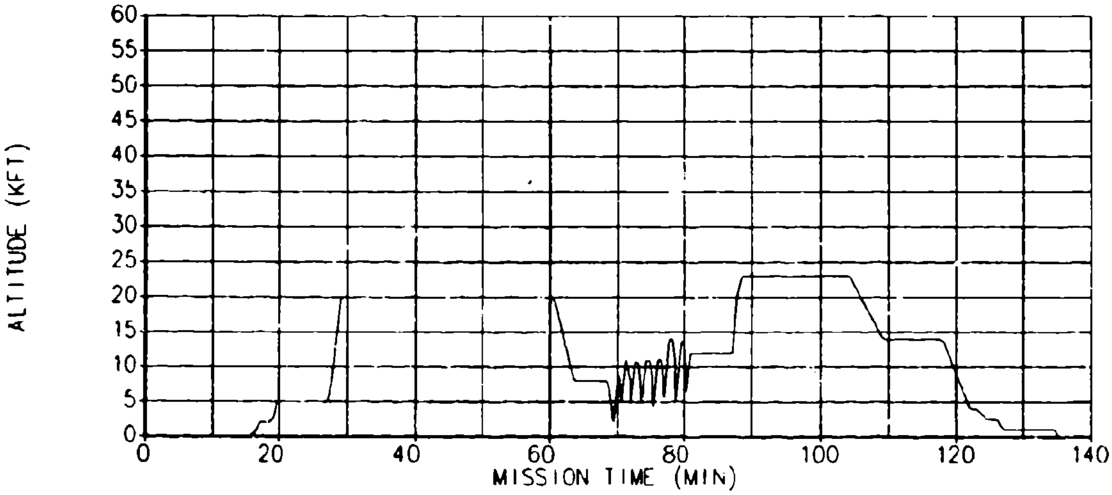
	SEGMENT	ALTITUDE (ft x 1,000)	MACH NUMBER	DISTANCE (nmi)
1	WARMUP/TAXI	0		
2	TAKEOFF	0.0 - 0.2	0.45	
3	SEGMENT CLIMB	0.2 - 20.0	0.4 - 0.6	
4	FORMATION CRUISE	20	0.5	250
5	REFUEL	20	0.49	
6*	SUBSONIC WEAPON DELIVERY	2 - 14	0.7 - 0.4	
7	FORMATION CRUISE	23	0.7	250
8	STAGED DESCENT	23 - 1	0.7-0.5	
9	LANDING	0	0.24	

b. *Proficiency*

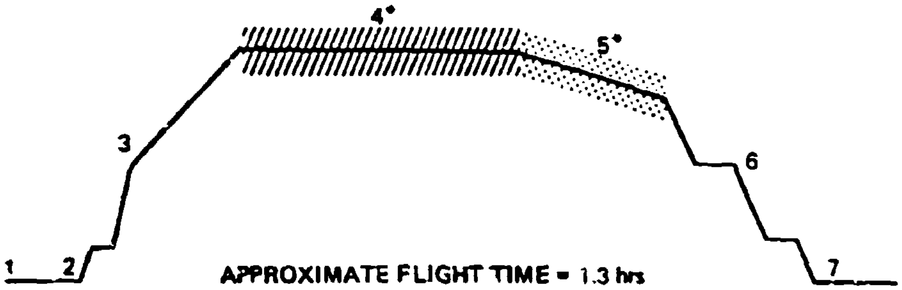
*Number of passes dependent on available fuel.

A-4. LUCID Mission 1: Subsonic Weapon Delivery Training





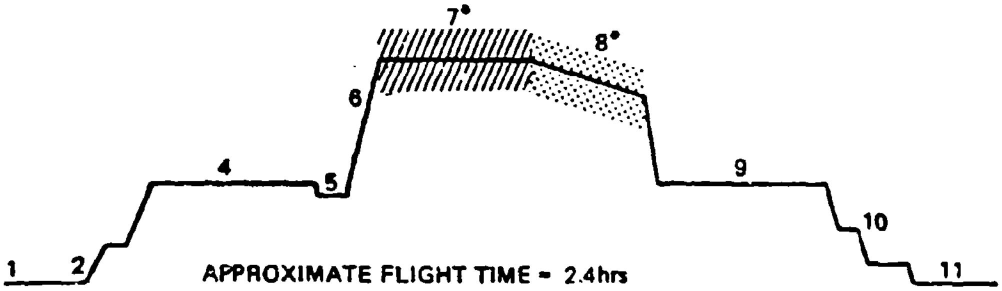
A-5. LUCID Mission 1B: Subsonic Weapon Delivery Training



SEGMENT		ALTITUDE (ft x 1,000)	MACH NUMBER	DISTANCE (nmi)
1	WARMUP/TAXI	0		
2	TAKEOFF	0-0.2	0.5	
3	ACCELERATION/CLIMB	0.2-45	0.5-2.19	25
4*	SUPERSONIC WEAPON DELIVERY	45-60	2.19-2.22	
5*	MISSILE AVOIDANCE ,REFUEL	60-50	2.22-0.6	
6	STAGED DESCENT	50-1.0	2.24-0.6	25
7	LANDING	1.0-0.0	0.24	

a. Initial

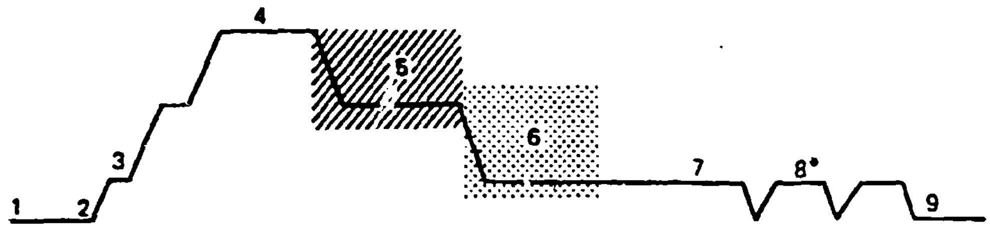
*Number of passes dependent on available fuel.



SEGMENT		ALTITUDE (ft x 1,000)	MACH NUMBER	DISTANCE (nmi)
1	WARMUP/TAXI	0		
2	TAKEOFF	0-0.2	0.5	
3	SEGMENT CLIMB ,REFUEL	0.2-20	0.5	
4	SUBSONIC CRUISE	20	0.55	250
5	REFUEL	20	0.50	
6	ACCELERATION/CLIMB	20-52	0.42-2.13	
7*	SUPERSONIC WEAPON DELIVERY	52-60	2.13	
8*	MISSILE AVOIDANCE	60-50	2.13	
9	SUBSONIC CRUISE	24	0.70	250
10	STAGED DESCENT	24-1.0	0.69-0.24	
11	LANDING	1.0-0.0		

b. Proficiency

A-6. LUCID Mission 2: Supersonic Weapon Delivery Training

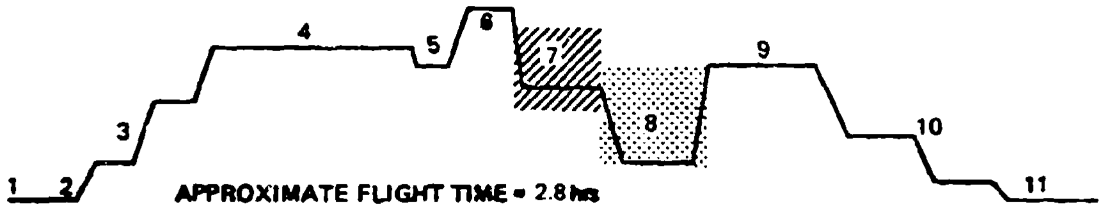


APPROXIMATE FLIGHT TIME = 1.4 hrs

	SEGMENT	ALTITUDE (ft x 1,000)	MACH NUMBER	DISTANCE (nmi)
1	WARMUP/TAXI	0		
2	TAKEOFF	0-2	0.5	
3	SEGMENT CLIMB	0.2-36.0	0.5-0.88	25
4	FAMILIARIZATION	36	0.6-0.9	
5	NAVIGATION–MID ALT	36-20	0.6-0.9	
6	NAVIGATION–LOW ALT	20-1	0.4-0.8	
7	LOW ALTITUDE CRUISE	1.0	0.4	25
8*	TOUCH & GOs	1.0-0.0	0.27	
9	LANDING	0		

*Number of passes dependent on avilable fuel.

a. Initial

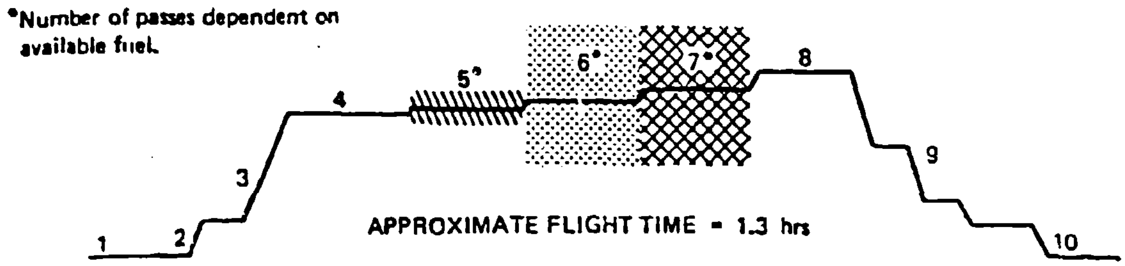


APPROXIMATE FLIGHT TIME = 2.8 hrs

	SEGMENT	ALTITUDE (ft x 1,000)	MACH NUMBER	DISTANCE (nmi)
1	WARMUP/TAXI	0		
2	TAKEOFF	0.0-0.2	0.5	
3	SEGMENT CLIMB	0.2-20	0.5	
4	FORMATION CRUISE	20	0.55	250
5	REFUEL	20	0.49	
6	FAMILIARIZATION	20-36	0.7-0.9	
7	NAVIGATION–LOW ALT	36-20	0.6-0.9	
8	NAVIGATION–MID ALT	20-1.0	0.4-0.8	
9	FORMATION CRUISE	23	0.7	250
10	STAGED DESCENT	23-1	0.4-0.26	
11	LANDING	1.0-0.0	0.24	

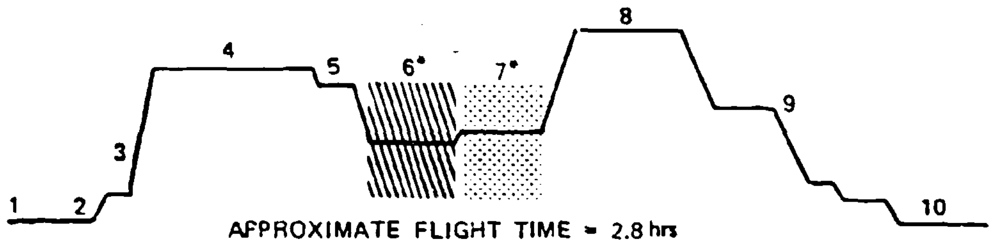
b. Proficiency

A-7. LUCID Mission 3: Familiarization/Navigation Training



SEGMENT		ALTITUDE (ft x 1,000)	MACH NUMBER	DISTANCE (nmi)
1	WARMUP/TAXI	0		
2	TAKEOFF	0 - 0.2	0.5	
3	SEGMENT CLIMB	0.2 - 15	0.5-1.2	
4	CRUISE ,REFUEL	15	0.5	25
5*	ACM - CONSTANT ALTITUDE	15	0.95 - 0.55	
6*	ACM - FREE	10 - 20	1.0 - 0.5	
7*	ACM - LEAD	15 - 22	0.8 - 0.4	
8	CRUISE ,REFUEL	15	0.6	25
9	STAGED DESCENT	15 - 1.0	0.5-1.2	
10	LANDING	1.0 - 0.0	0.25	

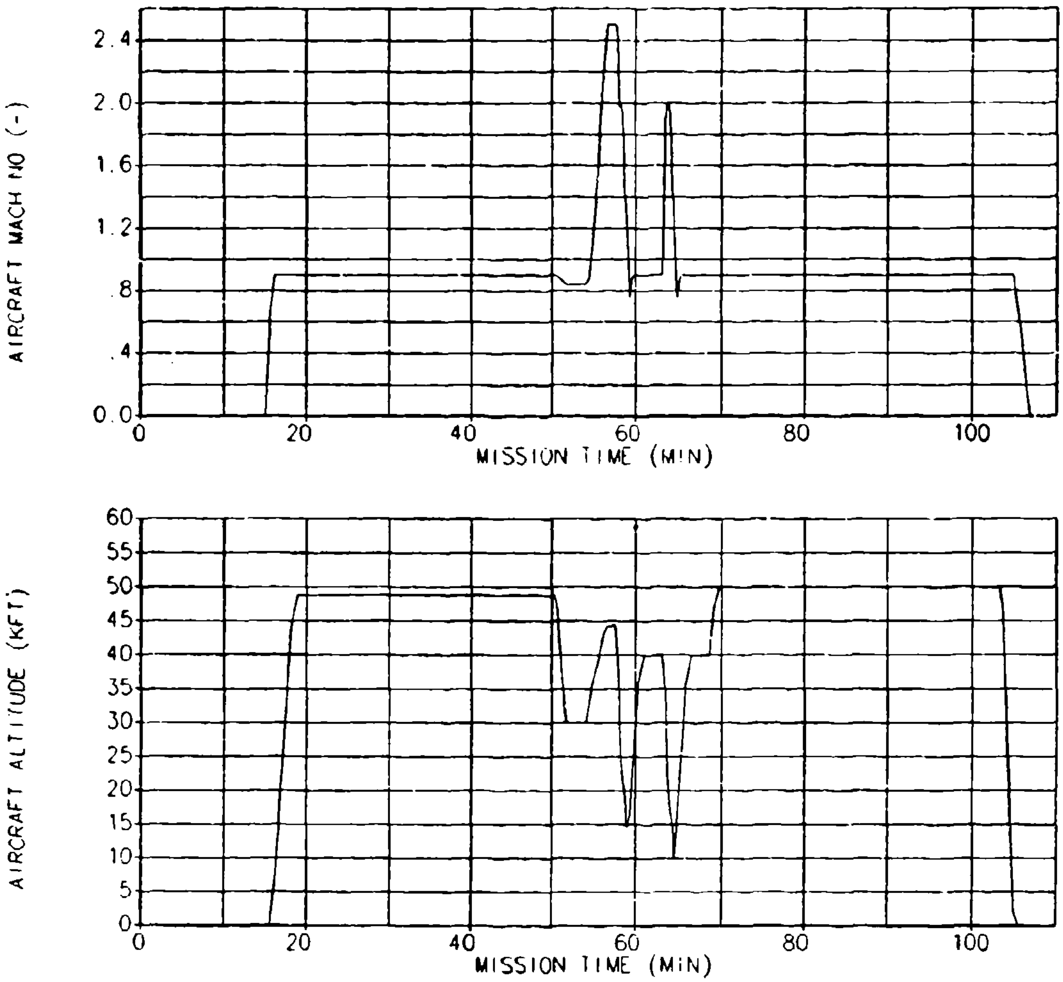
a. Initial



SEGMENT		ALTITUDE (ft x 1,000)	MACH NUMBER	DISTANCE (nmi)
1	WARMUP/TAXI	0		
2	TAKEOFF	0.0 - 0.2	0.5	
3	SEGMENT CLIMB	0.2 - 20	0.5	
4	FORMATION CRUISE	20	0.55	250
5	REFUEL	20	0.5	
6*	ACM - FREE	10 - 20	1.0 - 0.4	
7*	ACM - LEAD	10 - 20	1.0 - 0.4	
8	FORMATION CRUISE	23	0.7	250
9	STAGED DESCENT	23 - 1.0	0.7-0.24	
10	LANDING	1.0 - 0.0	0.22	

b. Proficiency

A-8. LUCID Mission 4: Air Combat Training Mission Profile



A-9. Escort Intercept Scenario: Air-to-Air Combat

APPENDIX B - FUEL TANK INERTING MISSION ANALYSIS CODE

B.1 Description of the Fuel Tank Inerting Mission Analysis Code

The Fuel Tank Inerting Mission Analysis code (FTIMA) solves for nitrogen, oxygen and fuel vapor concentrations in the ullage and dissolved nitrogen and oxygen in the fuel for small increments of mission time for both a stored gas and demand OBIGGS. For each incremental time step the following assumptions apply for the analysis (Ref. 10 and 14):

- o ideal gas law behavior
- o dissolved gases come into pressure equilibrium immediately in response to pressure changes in the ullage
- o solubilities of oxygen and nitrogen in the fuel are given by the temperature dependent Ostwald coefficients
- o nitrogen and oxygen gases are vented from the ullage in proportion to their mole fractions
- o the fuel vapor partial pressure is a function of fuel temperature only
- o the tank total pressure remains constant during the time increment for venting and scrubbing processes
- o scrub, wash and repressurization gases are introduced at the prevailing temperature in the tank.

The sequence for each incremental analysis time is:

- o update tank and ambient pressure temperature
- o compute changes in fuel dissolved gases due to scrubbing or washing
- o update partial pressures and concentrations in the ullage and fuel
- o evaluate ASM performance (output NEA quality and flow rate)
- o update time
- o update ambient and tank pressures and temperatures
- o test for refueling
- o test ullage total pressure; do one of the following:
  - o vent ullage gases
  - o take no action

    - o add repressurization gas
    - o add air (if necessary)
- o update ullage fuel partial pressures and concentrations
- o print results.

The largest NEA flow rate requirements are for tank repressurization. Descent rates, ullage volumes and temperatures, pressurization schedule and user defined NEA quality flow rate limitations have the largest effect on the NEA requirements and the resulting ullage oxygen concentration. The code will maintain the ullage pressure within the user defined restraints of the pressurization schedule as outlined here:

- o vent the ullage to maintain the maximum pressure defined by the climb valve
- o do nothing if the ullage pressure is less than climb valve pressure but greater than the demand regulator pressure, allowing the pressure to drop to the demand regulator setting
- o add repressurization gas to maintain the demand regulator setting subject to the flow rate limitation imposed by the user
- o if the repressurization flow rate is not great enough to pressurize the tank at the demand regulator setting, the internal tank pressure will decrease to the dive valve setting at which time air will be added to maintain the dive valve setting.

In conjunction with mission analysis the FTIMA will also evaluate pertinent OBIGGS performance parameters for each incremental time step. Namely:

- o ASM output flowrate and NEA quality
- o high pressure storage bottle for stored gas OBIGGS
    - o pressure
    - o temperature
    - o total mass stored
    - o NEA quality

These variables are used in the mission analysis in place of the user defined input for NEA concentration. The resulting ullage oxygen concentration is consequently a real simulation of the user defined OBIGGS variables consisting

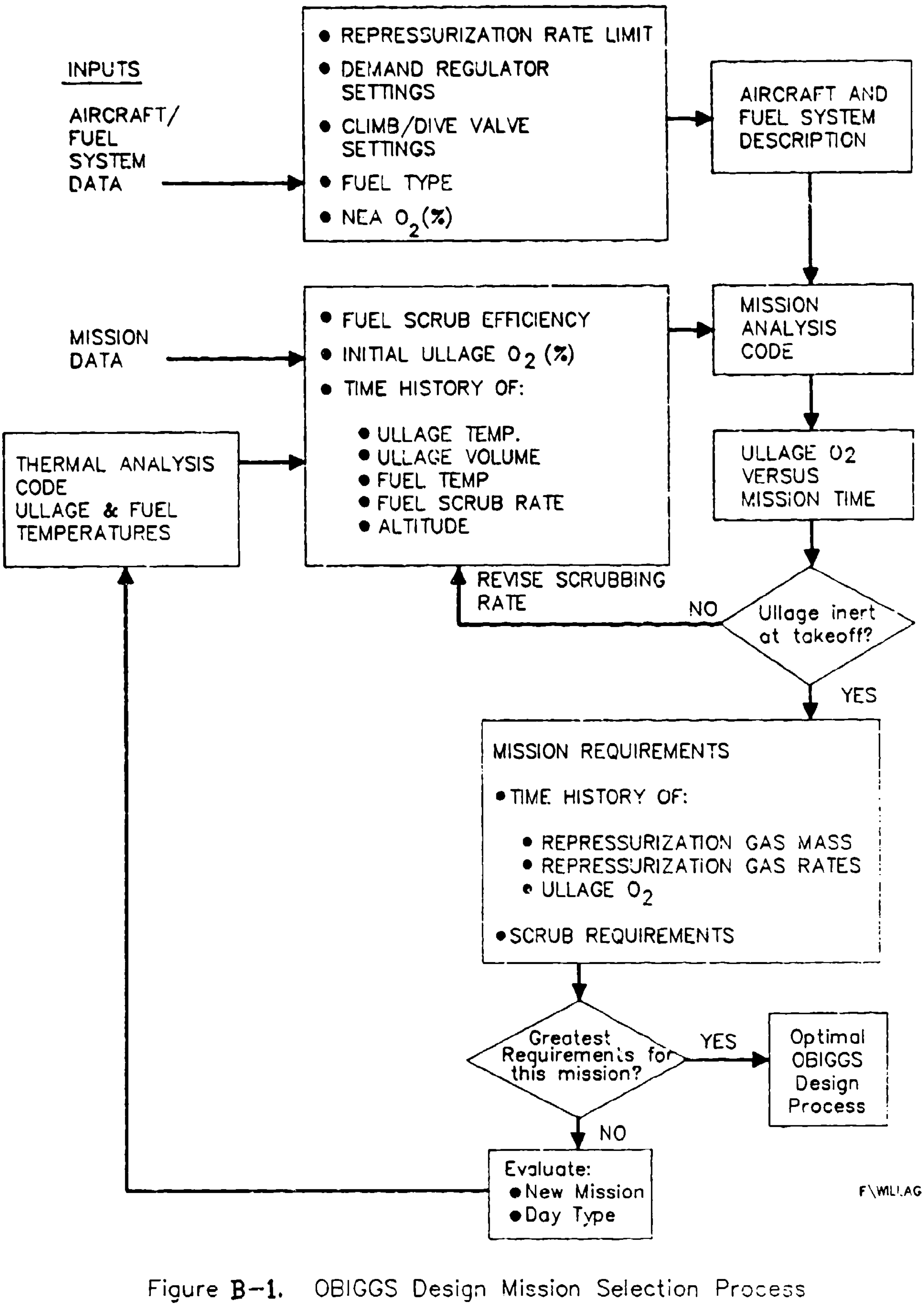


Figure B-1. OBIGGS Design Mission Selection Process

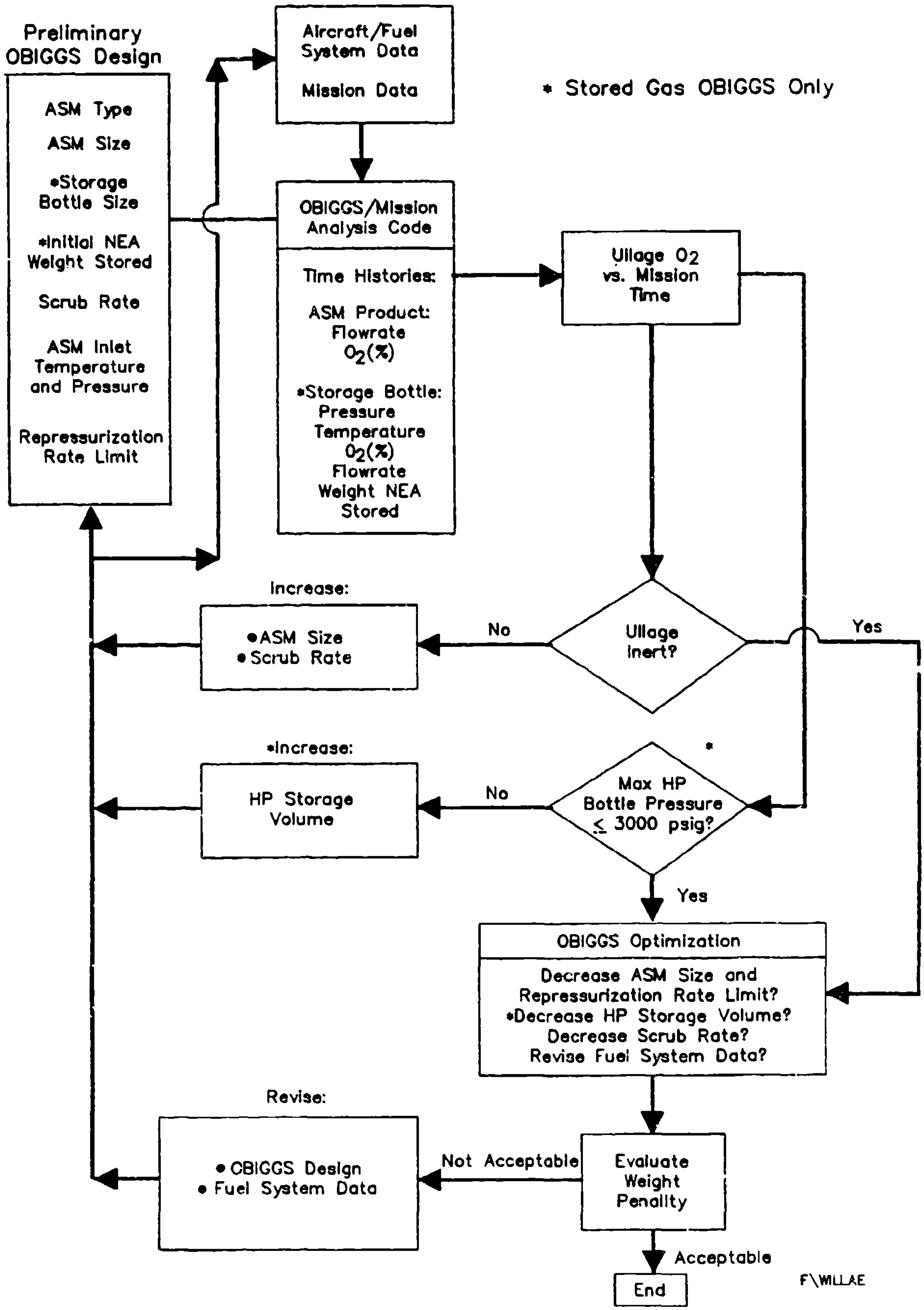


Figure B-2. Optimal OBIGGS Design Flow Chart

of:

- o size of ASM
- o high pressure storage volume for stored gas.

The OBIGGS weight can be evaluated for a stored gas or a demand OBIGGS as a function of:

- o ASM size and its maximum supply flow requirements
- o flow rate limitation of the NEA into the tank
- o high pressure storage volume for stored gas OBIGGS.

B.2 Use of Fuel Tank Inerting Code for OBIGGS Sizing

The FTIMA performs all the analysis functions vital to optimal OBIGGS design. Namely:

- o design mission selection of analysis
- o total NEA requirements
  - o scrub wash
  - o repressurization rate
  - o repressurization weight
  - o ground standby
- o OBIGGS performance, sizing and weight evaluation
  - o trade studies
  - o ASM size
  - o storage requirements
  - o OBIGGS weight penalty

The OBIGGS design process summarized in Figures E-1 and E-2 is accomplished by successive iterations of the FTIMA to determine the optimal OBIGGS which can inert the ullage in the worst case mission with the minimal weight penalty. The FTIMA will evaluate the OBIGGS performance and weight penalties for a stored gas and an on-demand OBIGGS.

The major criterion for mission selection is the appropriate NEA requirements evaluation. For the stored gas OBIGGS the greater the number and magnitude of altitude excursions the greater the repressurization requirements. This coupled

with the scrub or wash requirements would be the major sizing criteria for a stored gas OBIGGS. A demand OBIGGS is sized by the repressurization rate requirements. The user would use FTIMA to evaluate mission requirements directly by setting the appropriate flags in the input files. Determining the scrub requirements is an iterative process where the user makes an initial estimate for the scrub flow rate and scrub gas oxygen concentration runs the code and examines the ullage oxygen concentration. If the ullage oxygen concentration rises above 9% after the initial climbout, the program is rerun with a higher scrub flow rate. This process is repeated until the ullage remains inert. Preliminary trade studies can also be conducted in this phase of evaluation. This process is repeated for all candidate missions. The mission with the maximum total NEA mass and flow rate requirements would be the design mission for the stored gas and demand OBIGGS respectively.

OBIGGS performance and weight evaluations can also be conducted with the code. In this mode a pre-selected system can be evaluated or the code can predict the particulars of the OBIGGS such as ASM size and storage bottle size for a stored gas system. The code uses performance equations for the selected ASM type and predicts the ullage oxygen concentration from the mission analysis.

The pertinent output of the code is ullage oxygen concentration with performance information such as product flow rate and quality for both a stored gas system and high pressure bottle, temperature, accumulated stored mass and quality of NEA for the stored gas system.

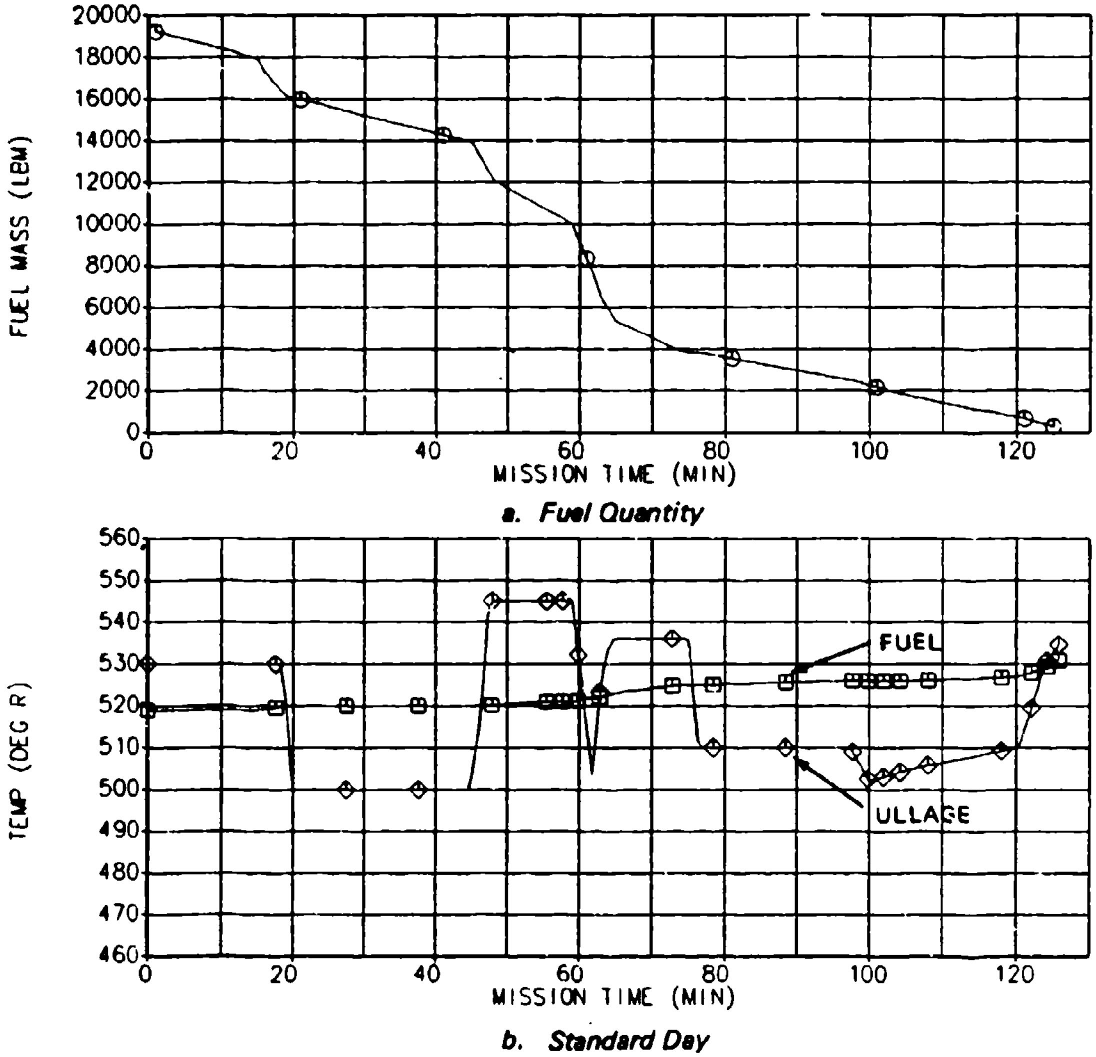
APPENDIX C - Temperature and Fuel Quantity Profiles

The computer code Airplane Fuel Tank Thermal Analysis (AFTTA), using the mission profiles shown in Appendix A, and the fuel quantity time histories (shown here), was used to predict the ullage and fuel temperature and time histories contained in this appendix. This information was used as input to the Fuel Tank Inerting Analysis code for mission analysis. The following assumptions applied to the use of AFTTA:

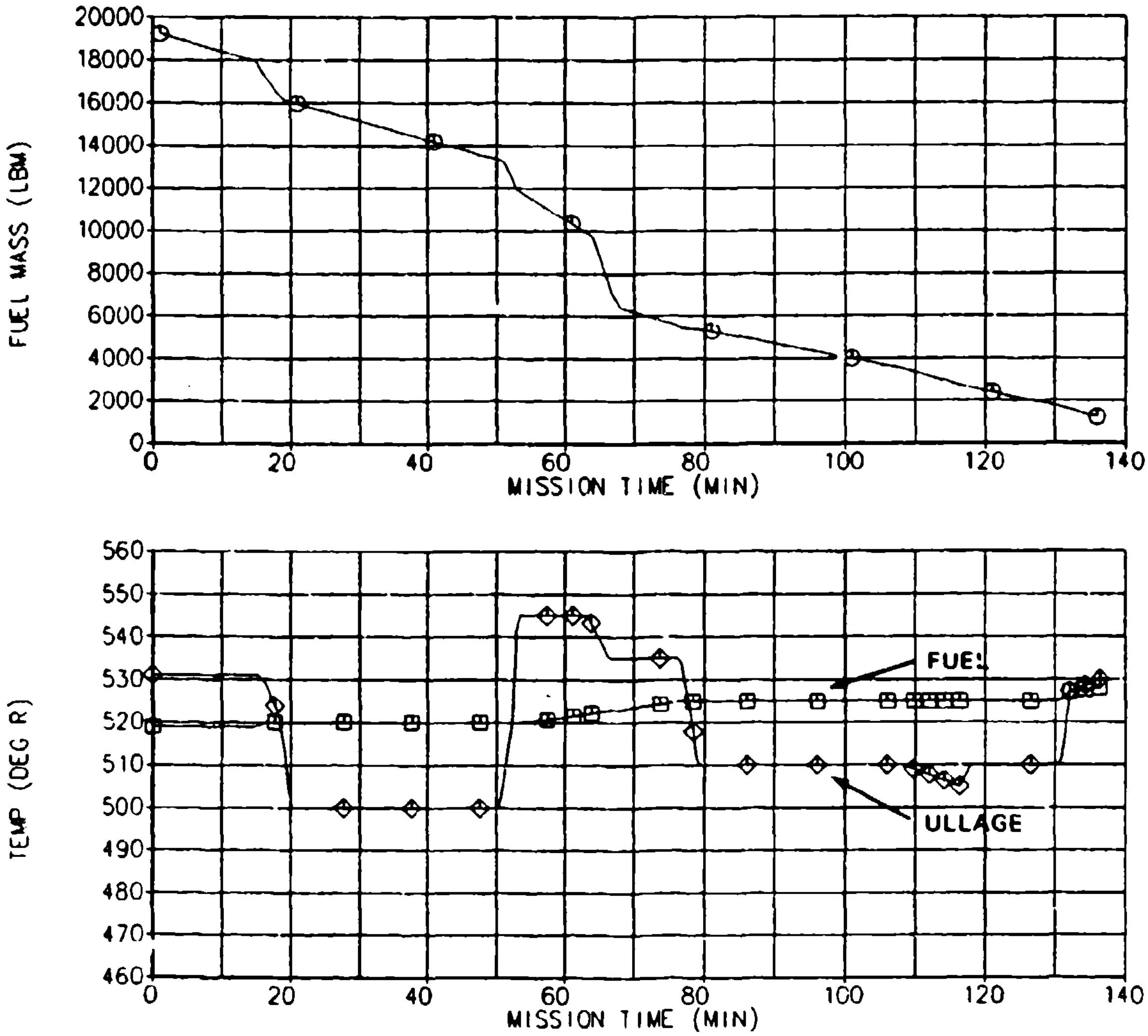
- 213 BTU/min of heating from onboard sources were added to the fuel
- all the fuel tanks were modeled as a single cylindrical tank with the airflow parallel to its axis
- tank walls are composite construction, dark in color.

These calculations were performed only for the five selected study missions, for reference:

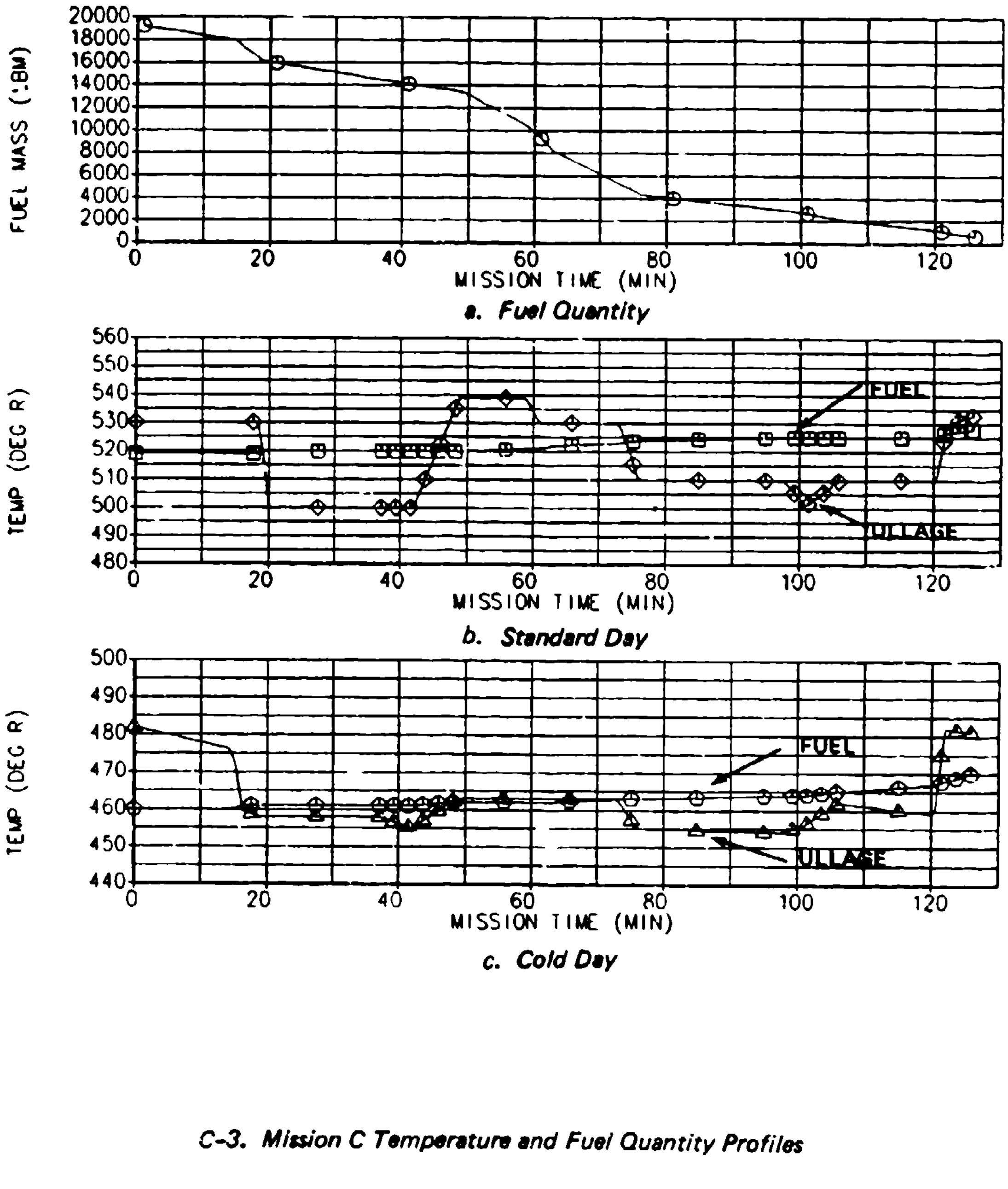
Label	Mission
A	PATS Mission 1
B	PATS Mission 2
C	PATS Mission 3
D	Training Mission 1B
E	Air-to-Air Combat



C-1. Mission A Temperature and Fuel Quantity Profiles



C-2. Mission B Temperature and Fuel Quantity Profiles

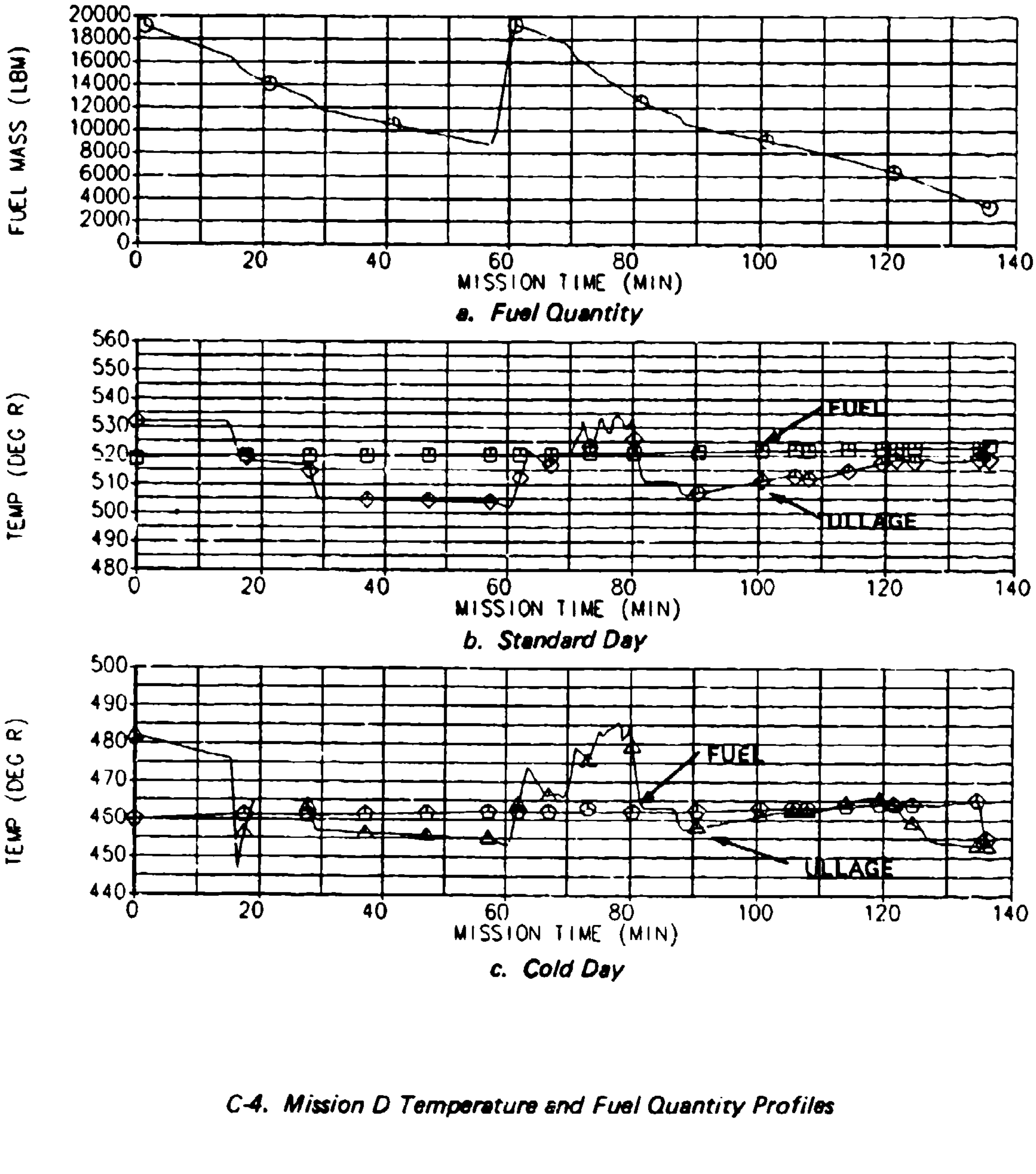


a. Fuel Quantity

b. Standard Day

c. Cold Day

C-3. Mission C Temperature and Fuel Quantity Profiles

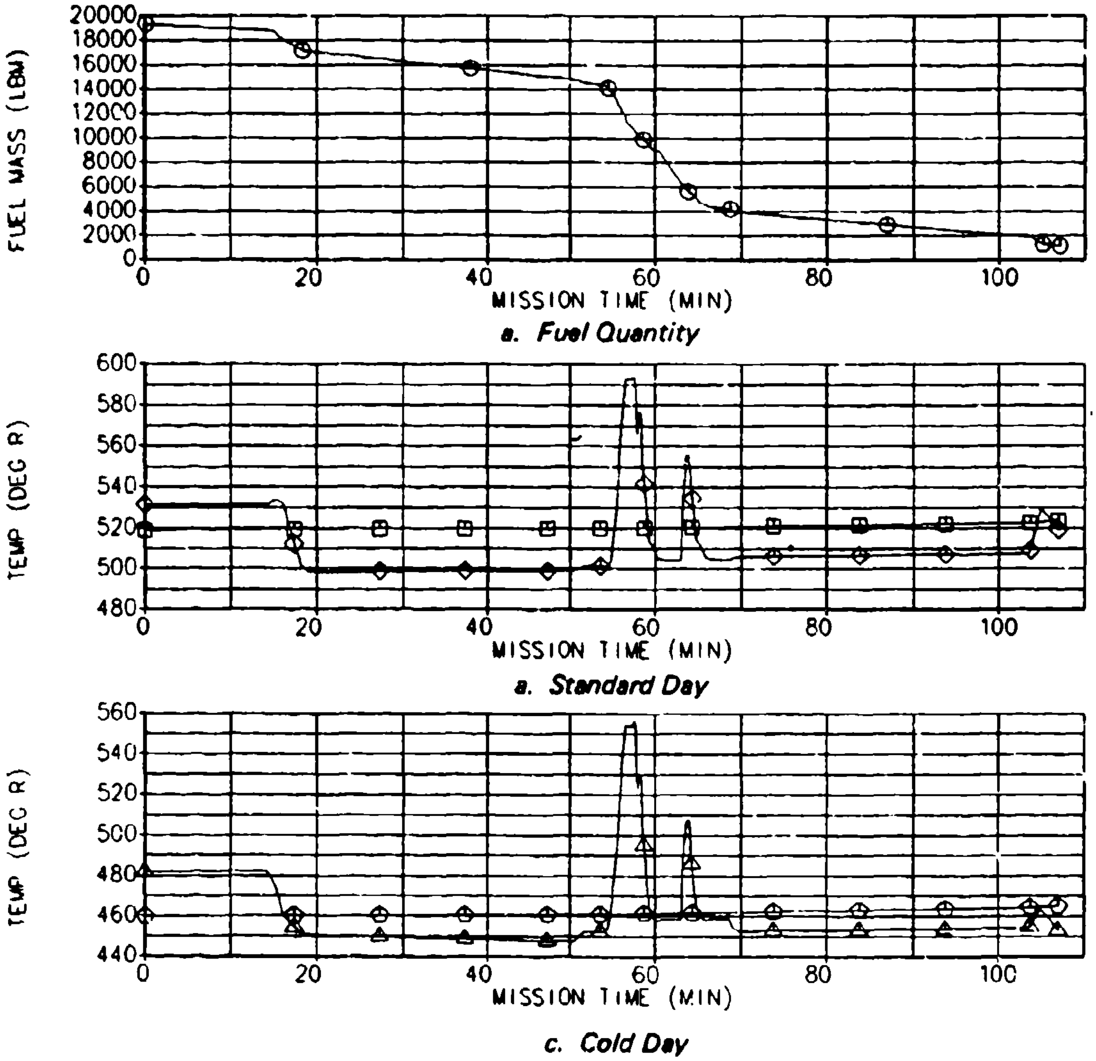


a. Fuel Quantity

b. Standard Day

c. Cold Day

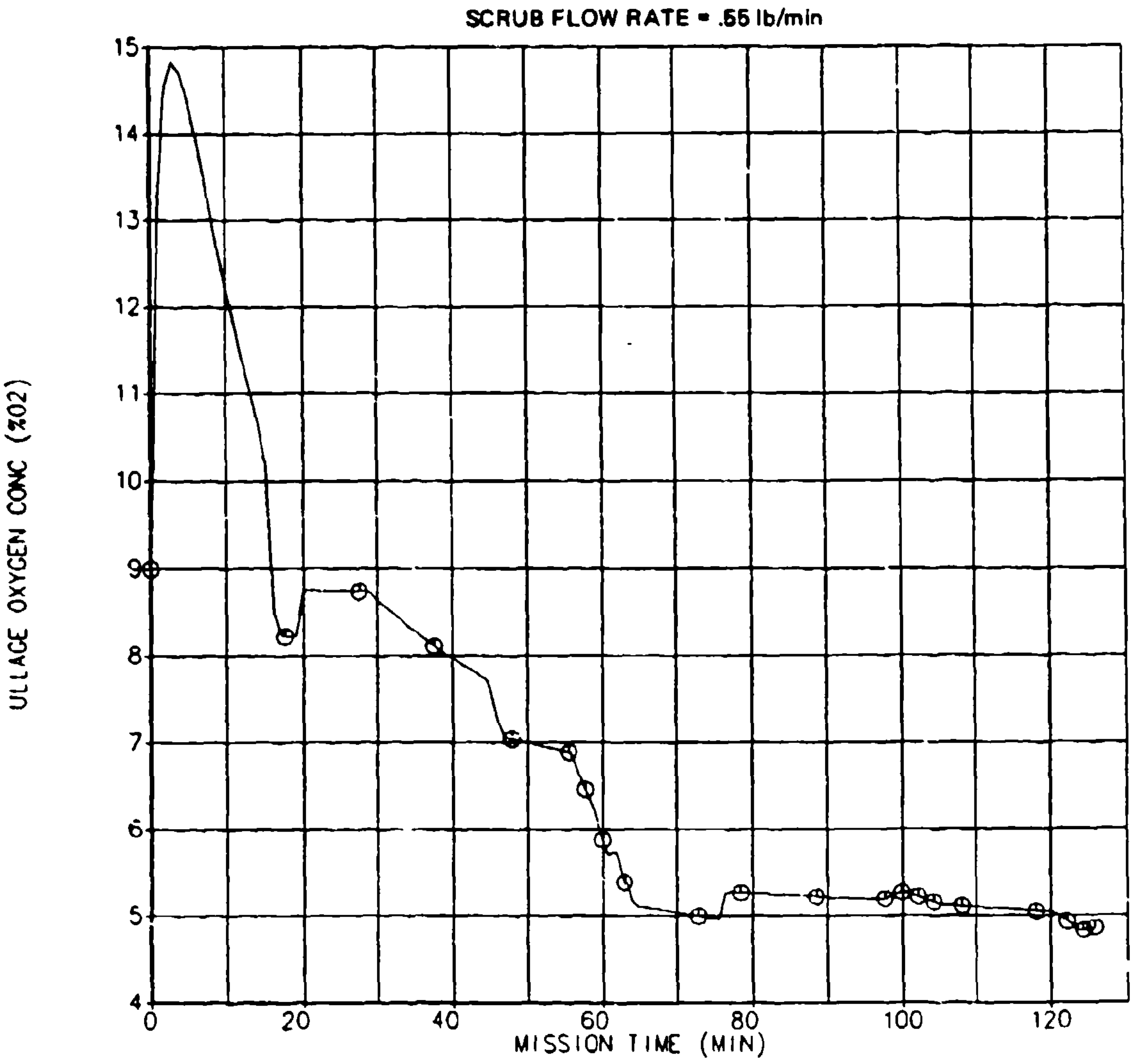
C-4. Mission D Temperature and Fuel Quantity Profiles



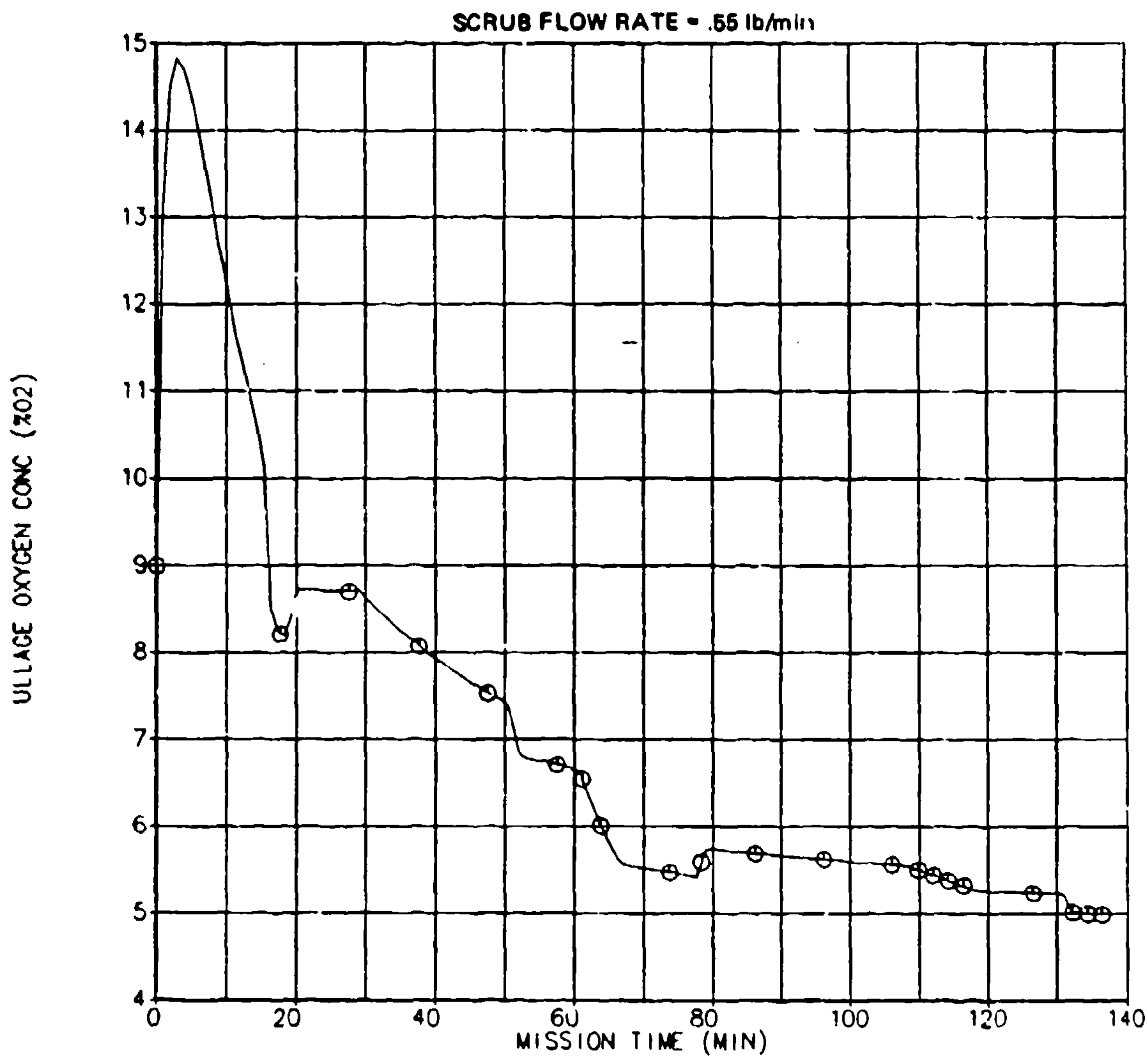
C-5. Mission E Temperature and Fuel Quantity Profiles

APPENDIX D - Ullage Oxygen Concentration Profiles

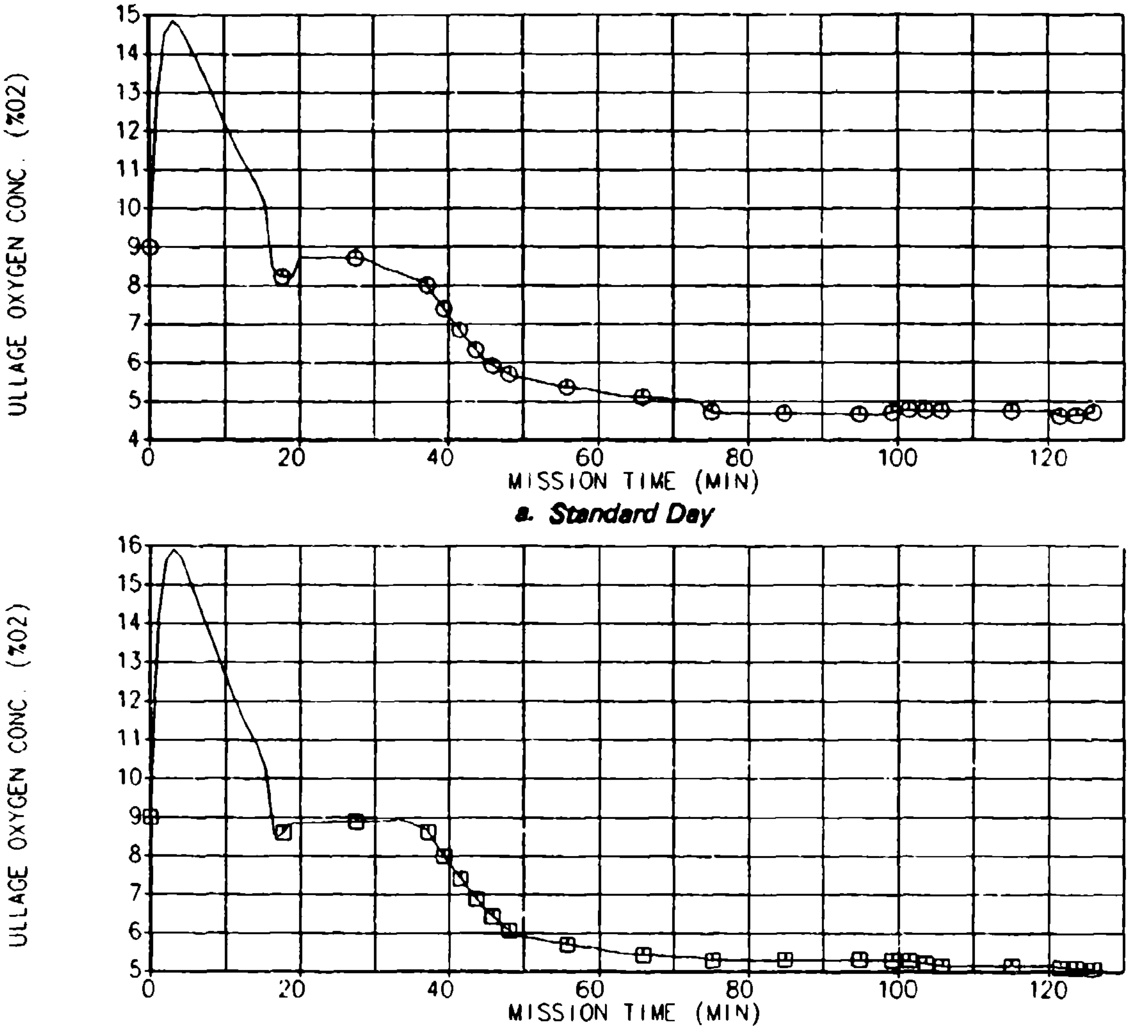
Contained in this appendix are the plots of ullage concentration versus mission time for the five study missions. This data is the basis for the fuel scrubbing analysis discussed in Section 3.3.1.



D-1. Ullage Oxygen Concentration for Mission A (Standard Day)

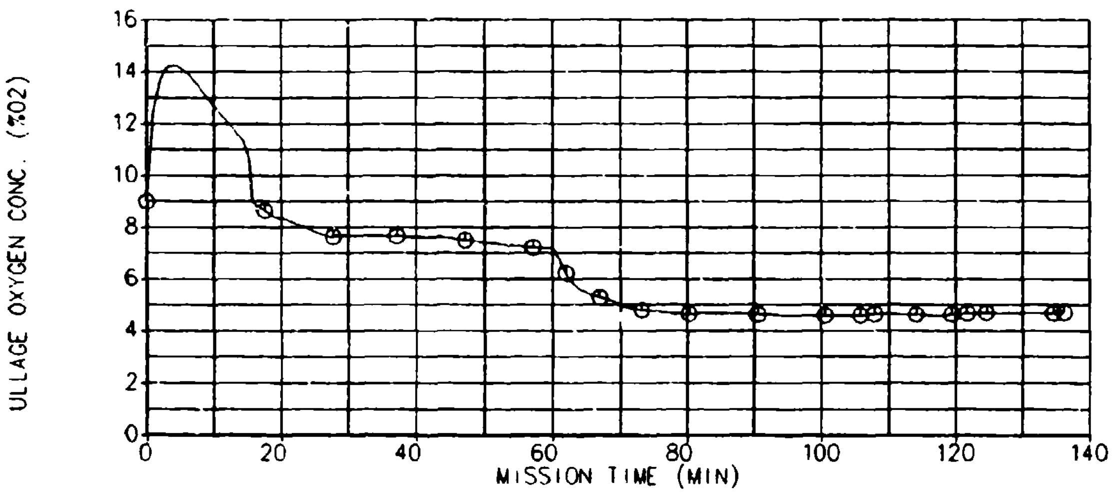


D-2. Ullage Oxygen Concentration for Mission B (Standard Day)

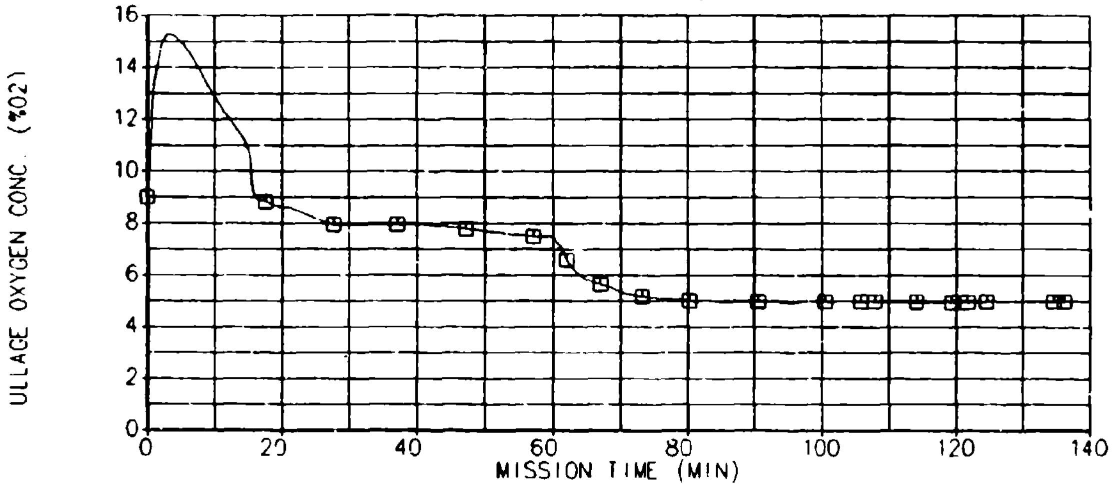


b. Cold Day

D-3. Ullage Oxygen Concentrartion for Mission C (Standard and Cold Day)

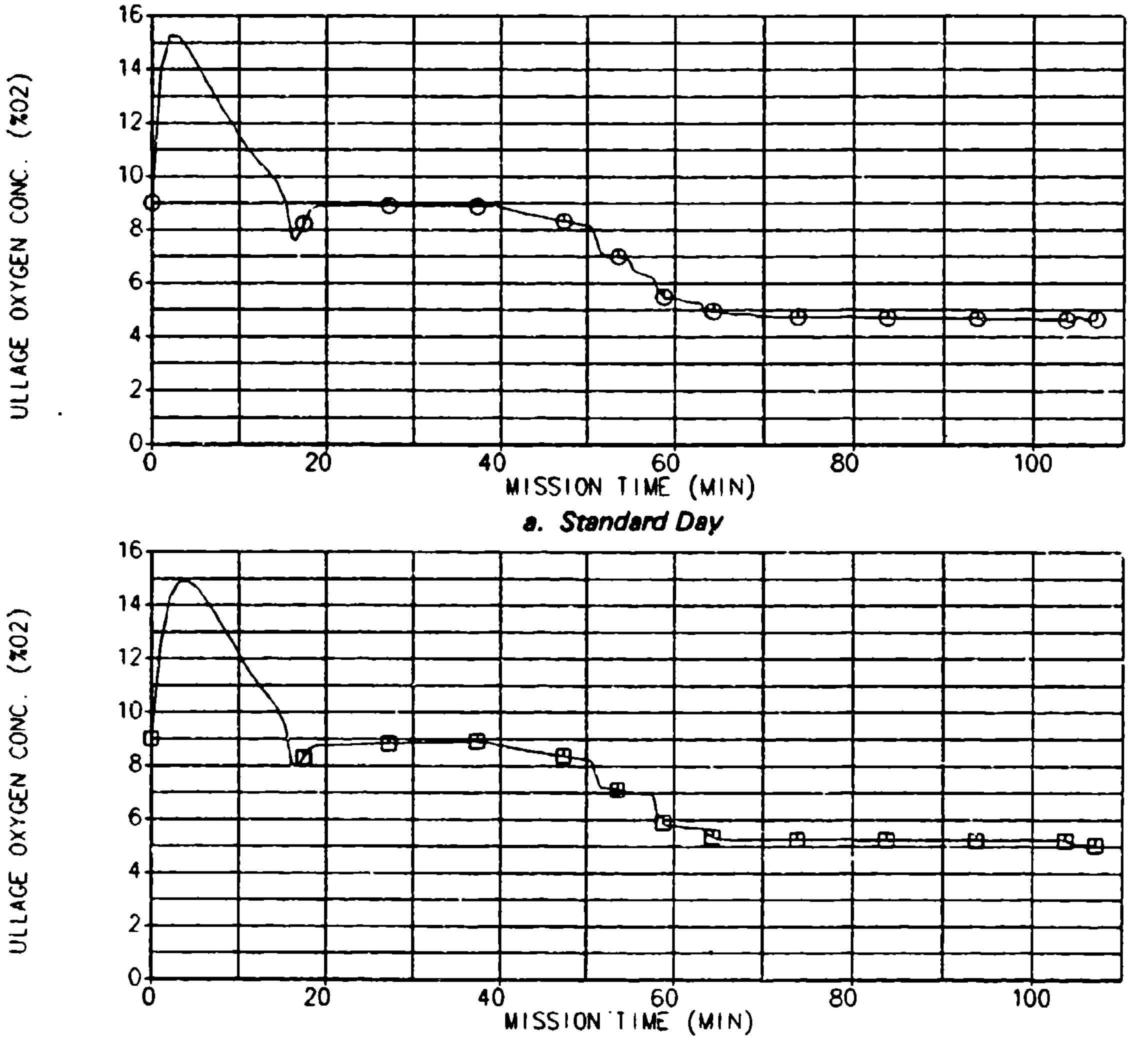


b. Standard Day



b. Cold Day

D-4. Ullage Oxygen Concentration for Mission D (Standard and Cold Day)



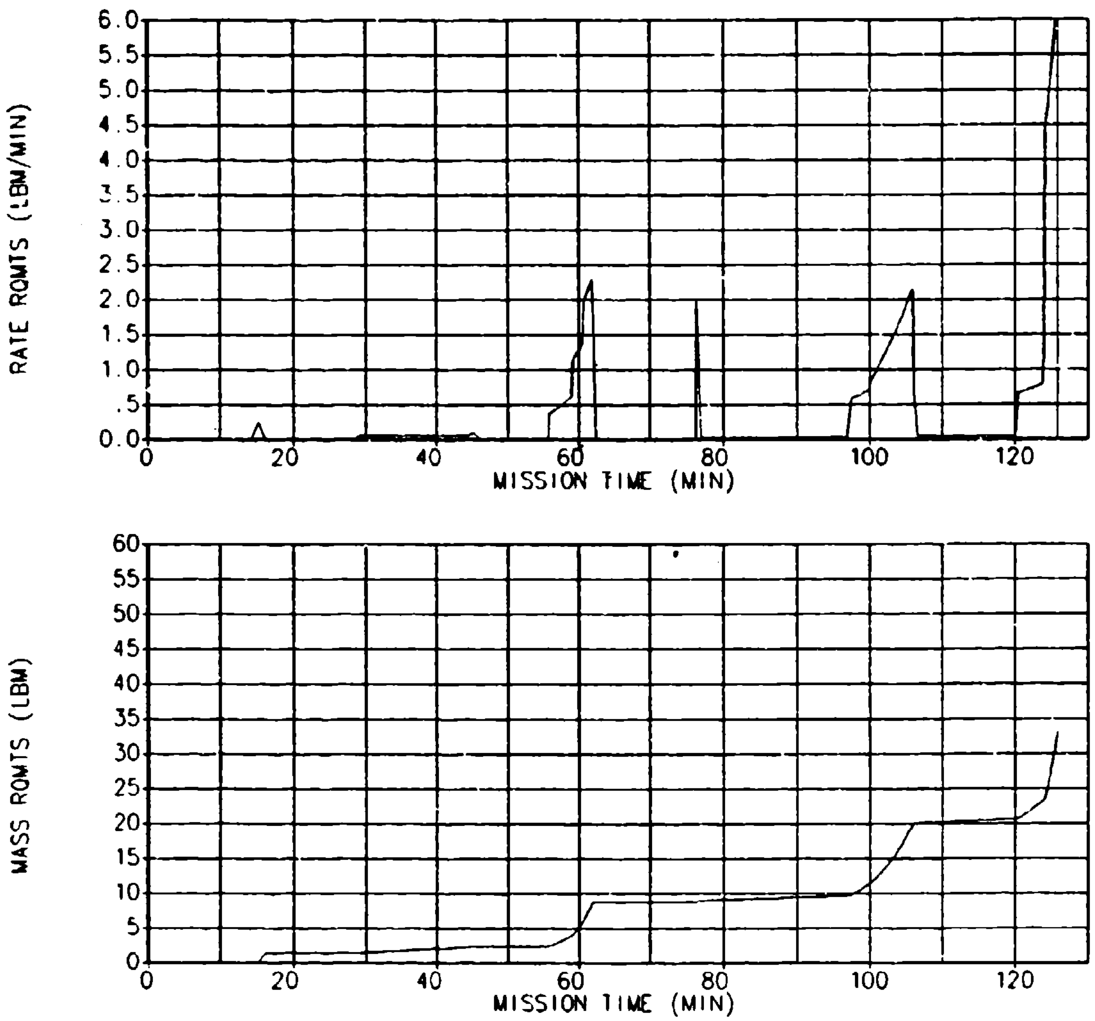
a. Standard Day

b. Cold Day

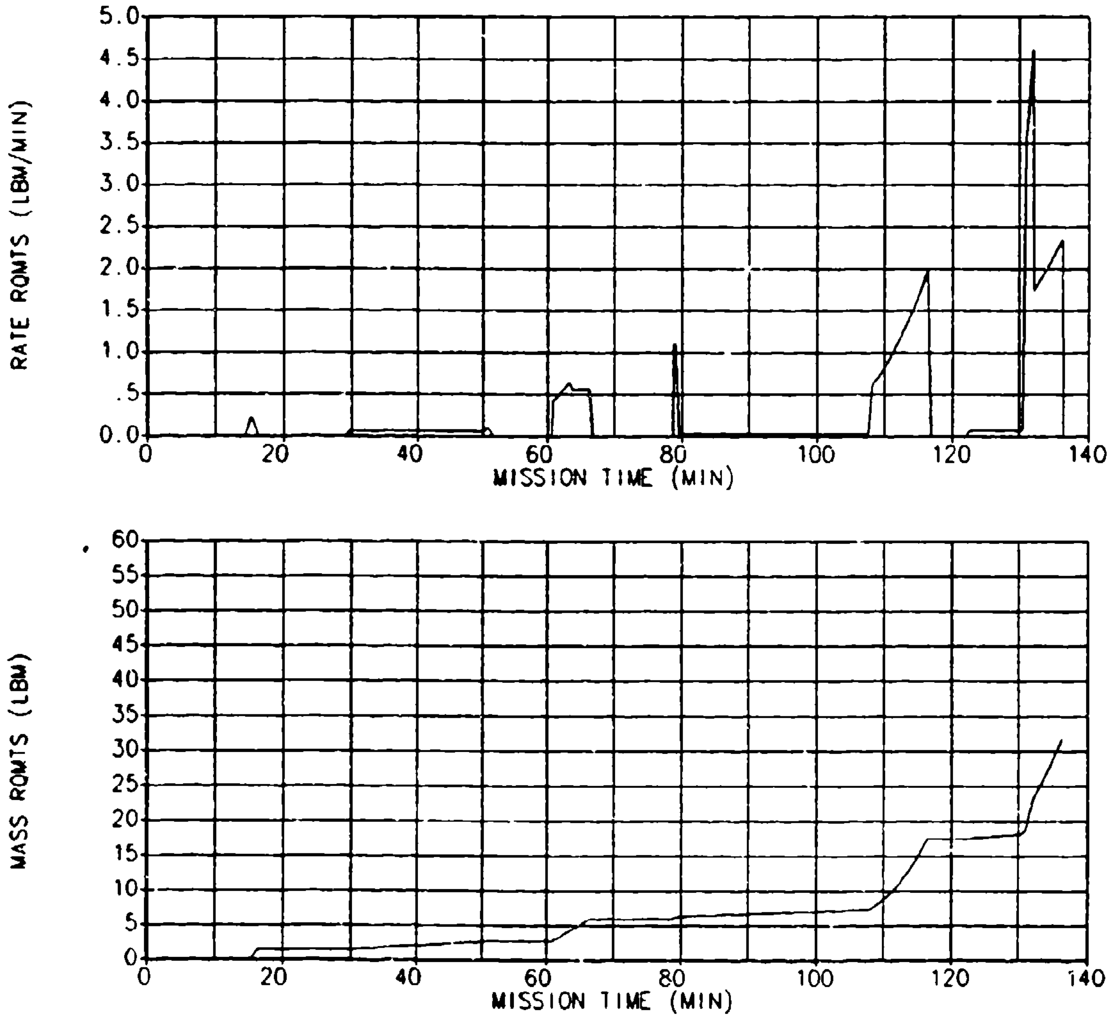
D-5. Ullage Oxygen Concentration for Mission E (Standard and Cold Day)

APPENDIX E - Descent Repressurization Requirement Data

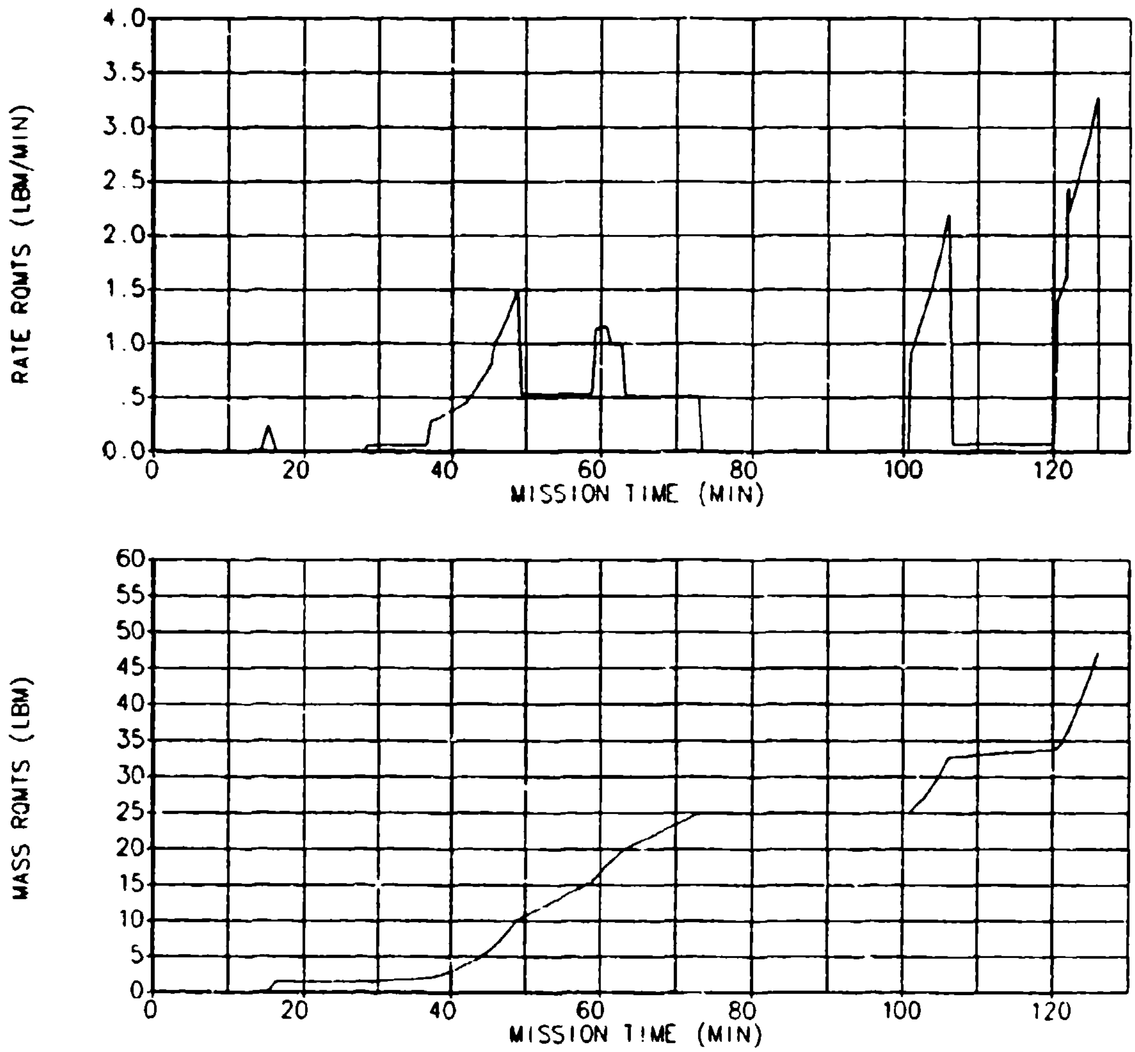
Results of the descent repressurization requirement analysis discussed in Section 3.3.2 are presented in this appendix.



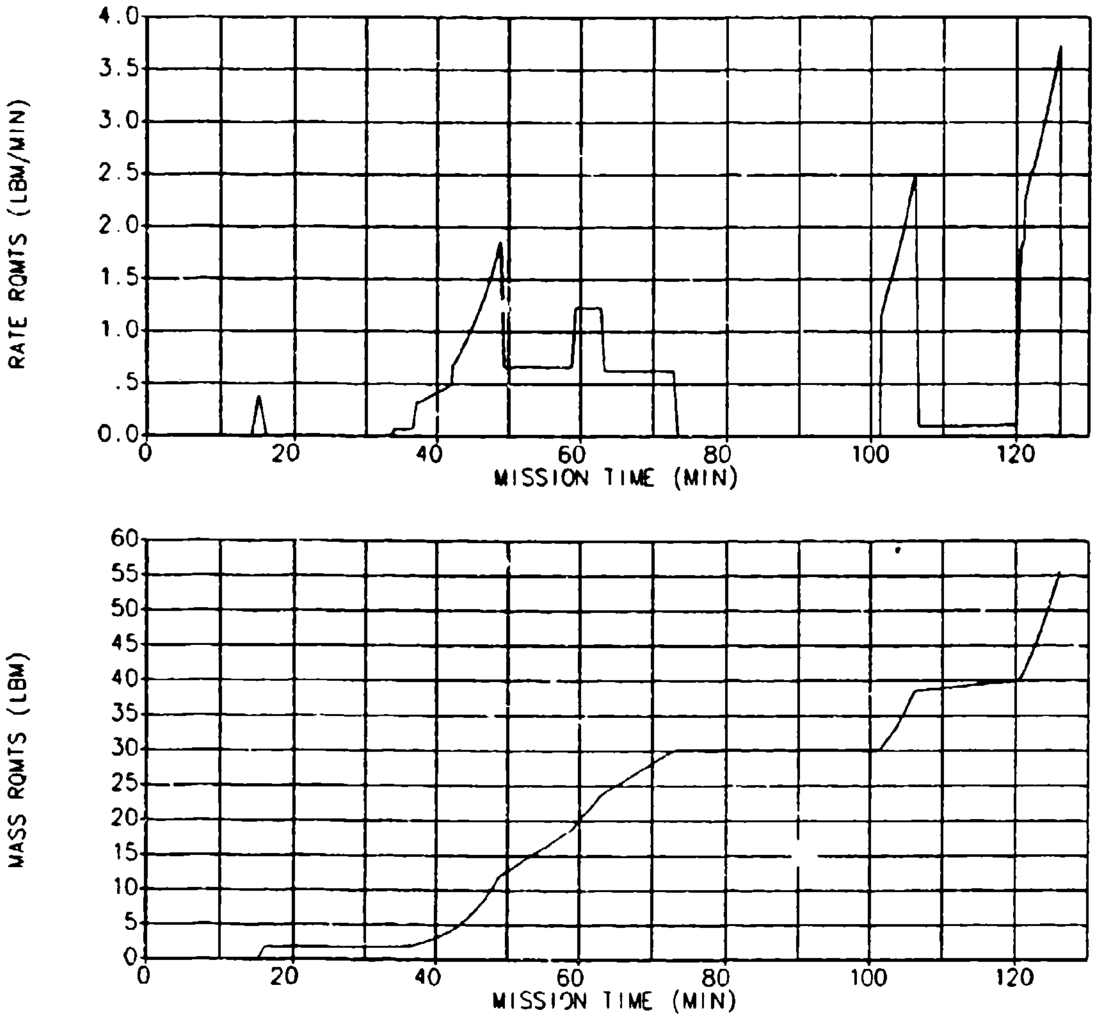
E-1. Repressurization Requirements for Mission A (Standard Day)



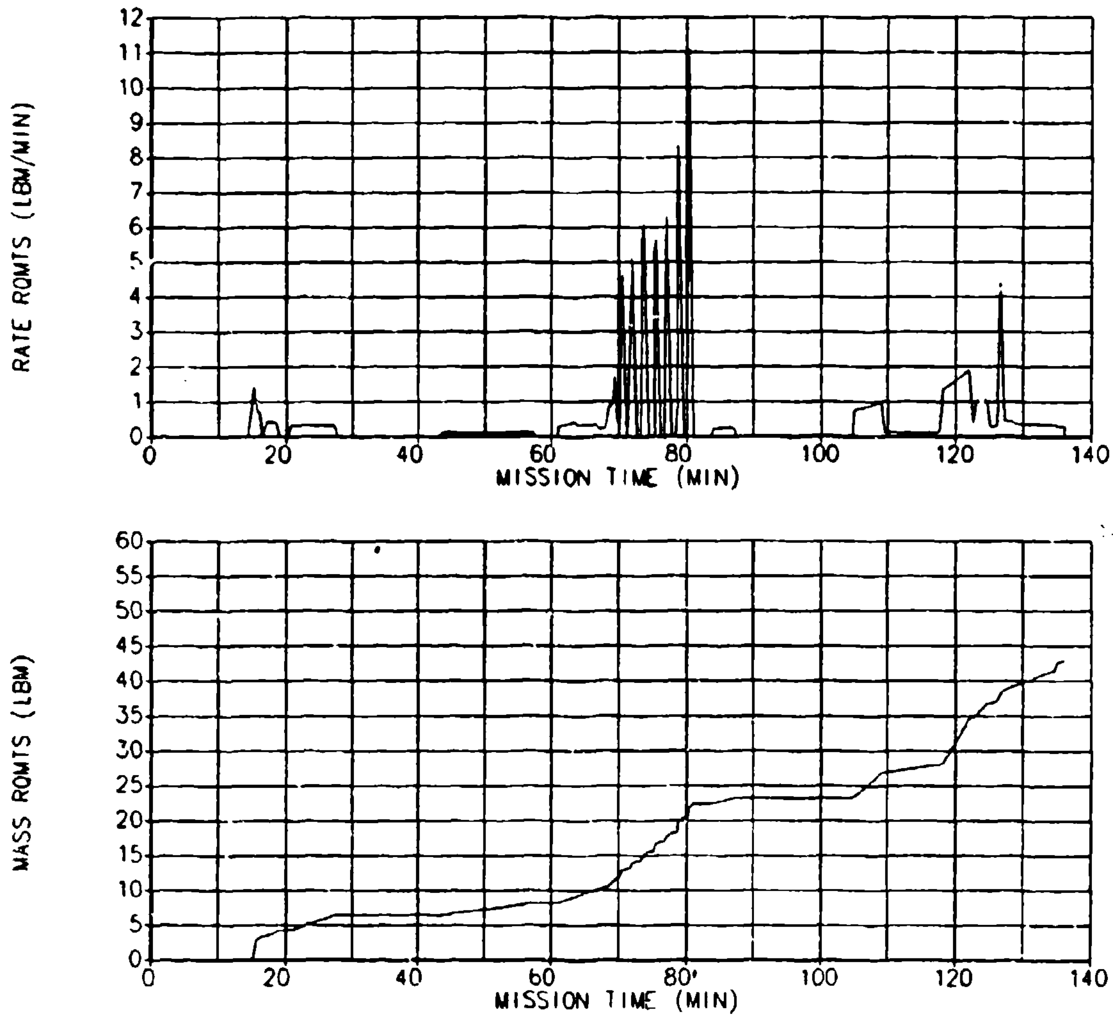
E-2. Repressurization Requirements for Mission B (Standard Day)



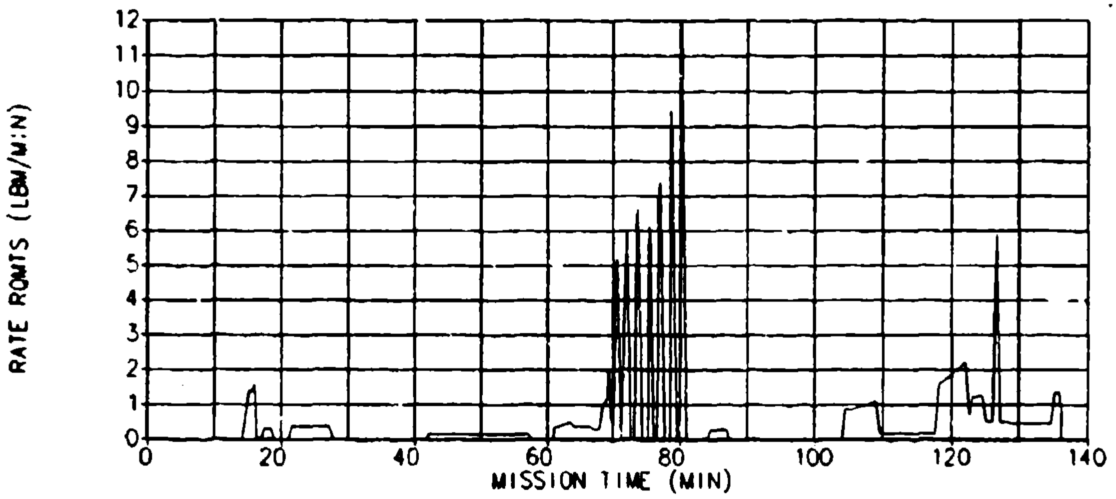
E-3a. Repressurization Requirements for Mission C (Standard Day)

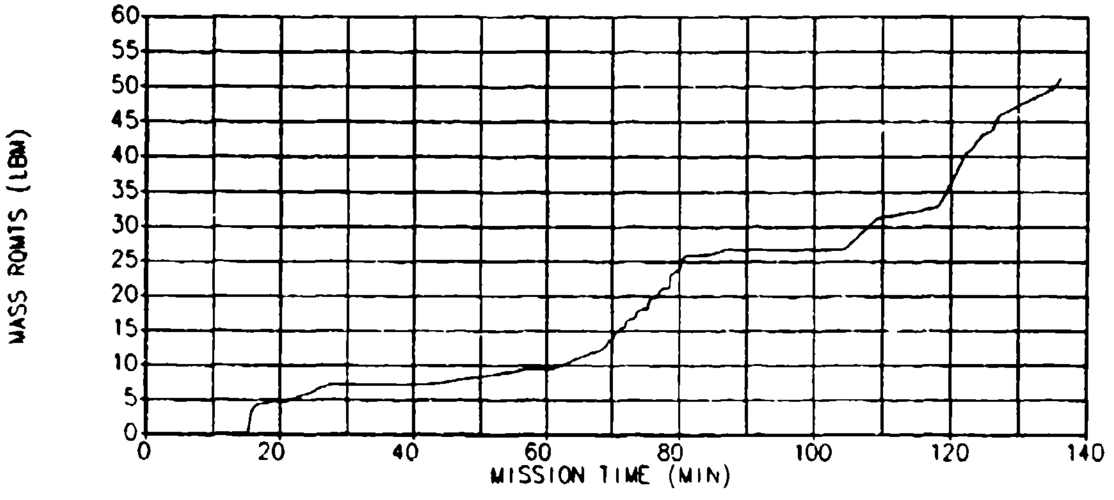


E-3b. Repressurization Requirements for Mission C (Cold Day)

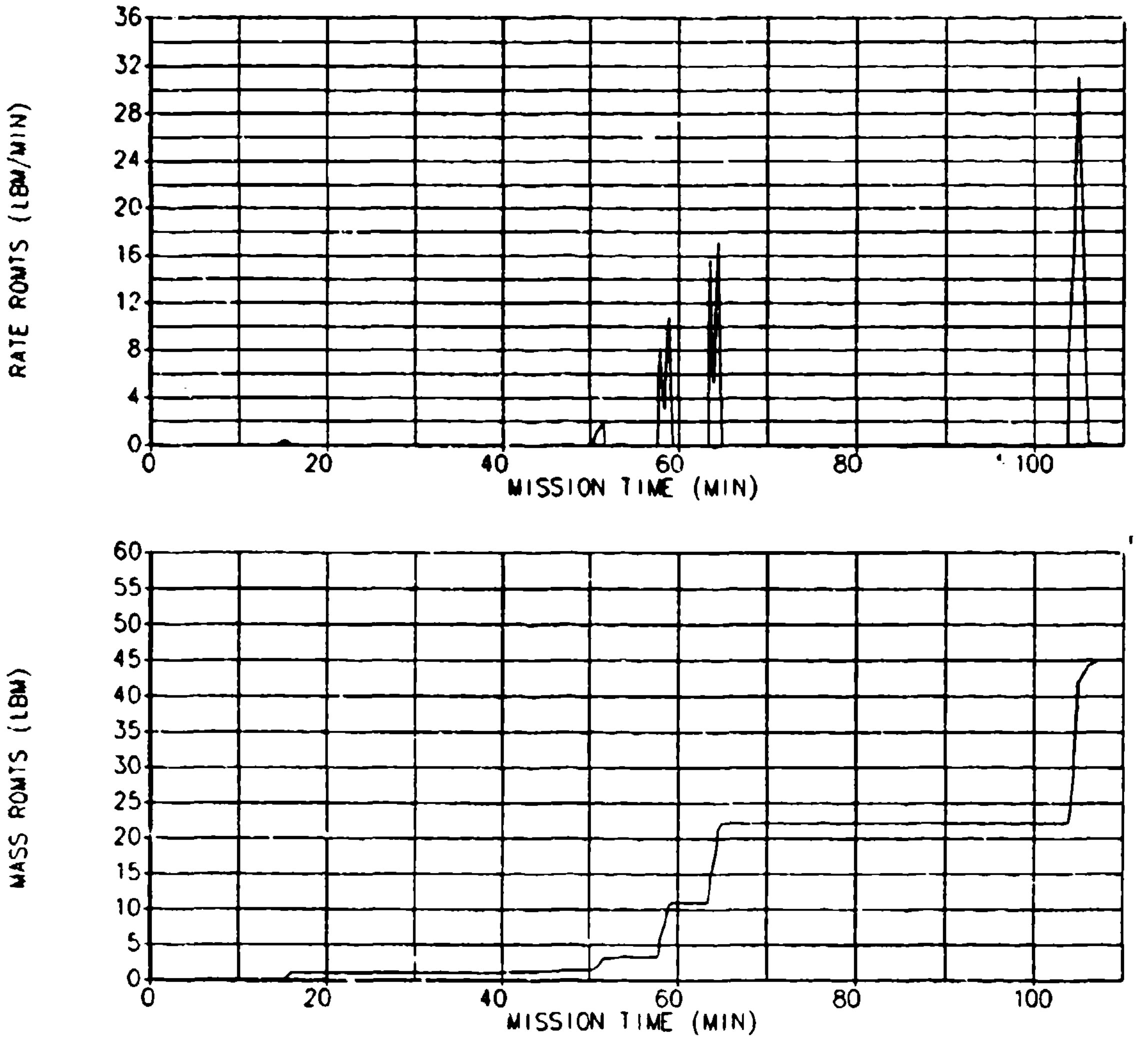


E-4a. Repressurization Requirements for Mission D (Standard Day)

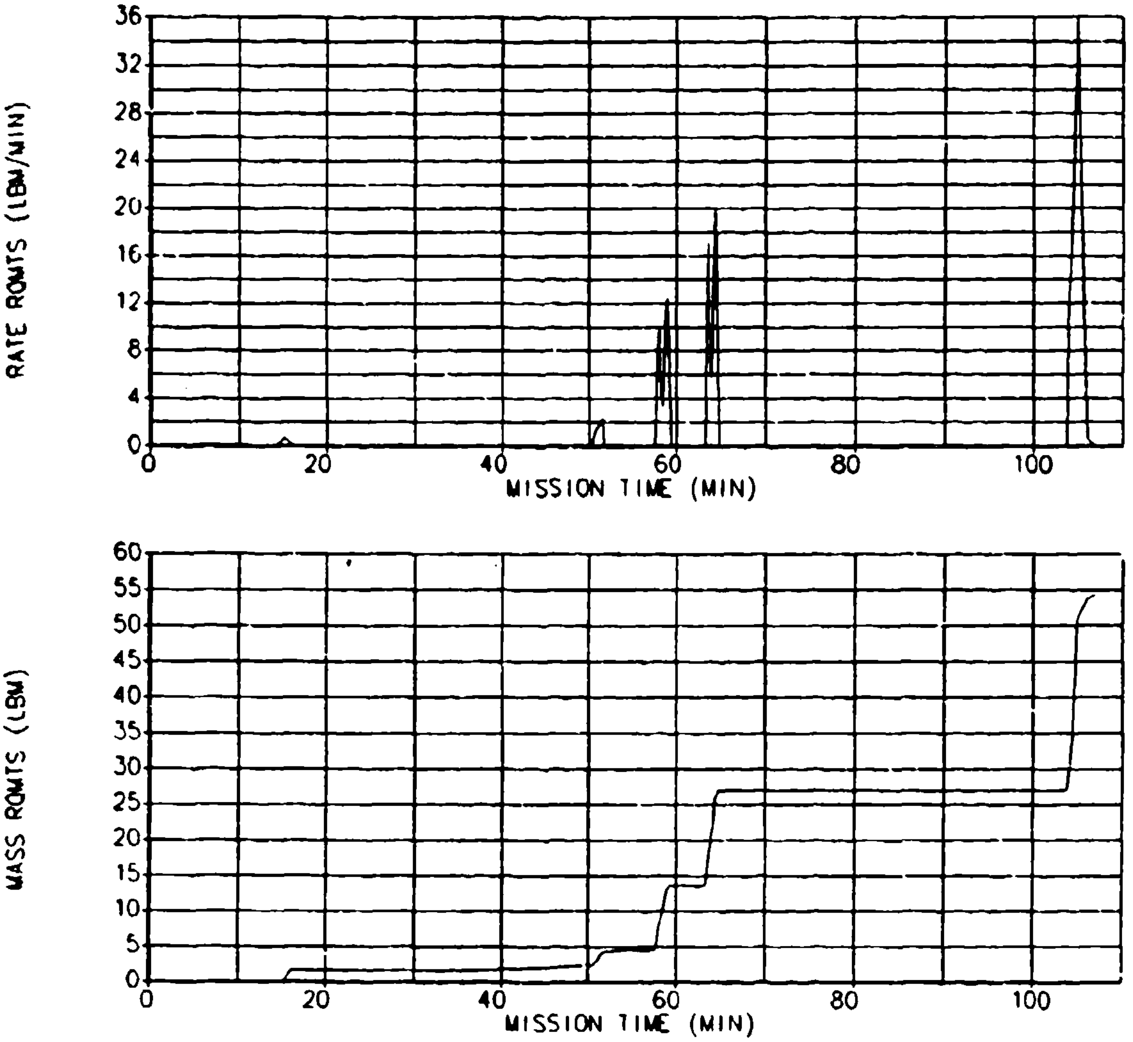




E-4b. Repressurization Requirements for Mission D (Cold Day)



E-5a. Repressurization Requirements for Mission E (Standard Day)



E-5b. Repressurization Requirements for Mission E (Cold Day)

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